

THE FERROMAGNETIC PROPERTIES OF HEMATITE

By

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INTRODUCTION

The problem of beneficiating American iron ores is not a new one and may be expected to become increasingly important with time. Reserves in the United States in May 1938¹ amounted to approximately 1,400,000,000 tons. With a yearly production of 50,000,000 tons this country has an assured production for only 25 or 30 years. This figure does not appear alarming until it is considered that the average grade of the reserves is trending downwards while the blast furnace operator still demands that the grade of the incoming ore be at least 50 percent iron. Even now mine operators are mixing lean ores with rich ores to hold the grade to about 51 percent and conserve the high-grade deposits. Obviously, when the grade of iron ore produced falls under this figure there will be an increase in the price of pig iron and a corresponding industrial readjustment in price for all finished iron products.

There are immense deposits of marginal ores--30 to 50 percent iron--in this country. If some cheap method of concentrating these ores could be found² the United States would be assured of iron supremacy for practically an indefinite period. It must be borne in mind that any concentration process developed must be cheap, efficient, and capable of handling large tonnages because the initial value of the iron ore is usually \$3 per ton or less. About 15 percent of our total yearly production comes from the beneficiation of certain iron ores, mainly by gravity methods, such as log washing and jigging. The large tonnage of

¹ United States Bureau of Mines Minerals Yearbook, 1939, section on iron ore production.

² Iron ore concentration processes are principally directed towards removing the greatest impurity, silica; little can be done in changing the phosphorus or sulfur content.

iron rejected by these methods leaves much to be desired from the metallurgical standpoint of percent recovered. Flotation³ has been tried on these wash-ore tailings, but it can hardly be said that it has progressed to the stage of commercial application. Of late, a sink and float process has shown interesting possibilities, but sufficient tonnage has not been handled as yet to establish the method. During the last few years a process^{4,5} has been developed on the Mesabi Range for roasting the hematite in a reducing atmosphere to produce magnetite, and then concentrating this on an ordinary direct current magnetic separator. The high cost of reducing the ore and subsequent briquetting of the concentrates restrict the use of this method to selected cases. In 1922, Mordey⁶ discovered a new action of alternating magnetic fields on ferromagnetic materials—new in respect to the fact that there was a repulsion of material from alternating magnetic poles as well as an attraction. This offers a potential means for concentrating hematite ores at a low cost per ton. In order to develop this idea practically, a knowledge of the magnetic properties of hematite is indispensable.

³ John N. Searles. Some Tests with Flotation on Mesabi Wash Ore Tailings. Eng. and Min. Jour., 1939, no. 6, 1938, pp. 42-44.

⁴ E. W. Davis. First Magnetic Roasting Plant in the Lake Superior Region. Amer. Inst. Min. and Met. Eng., Tech. Pub. 731, 1937.

⁵ J. J. Craig. Magnetic Concentration on the Mesabi Makes Progress. Eng. and Min. Jour., 139, no. 1, 1938, pp. 48-52.

⁶ W. W. Mordey. The Concentration of Minerals by Means of Alternating Electric Current. Min. Mag., 26, 1922, pp. 333-343.

As our knowledge of the magnetic properties of hematite was fragmentary and wholly inadequate for the purpose in view, it was essential to determine the hysteretic constants⁷ of hematite. This was the object of the work described in this paper.

⁷ The hysteretic constants are coercive force and remanence which we shall consider as characteristic exclusively of ferromagnetic substances.

LITERATURE

Although many investigators have worked with natural and artificial ferric oxide (Fe_2O_3), only a few have recognized the true ferromagnetic nature of hematite while many have ascribed the ferromagnetic effects to the presence of gamma hematite or "ferromagnetic ferric oxide".⁸ It is true that the crystal of hematite has preferred planes of magnetization,⁹ but that fact has little bearing on the present problem because most hematites are polycrystalline and for purposes of magnetic separation only a knowledge of total magnetization is necessary.

Koenigsberger¹⁰ in 1898 found hematite to be ferromagnetic but suspected that the magnetism was due to admixtures of magnetite although chemical analyses showed little or no FeO .

Westmann's¹¹ data, erroneously cited even in authoritative publications¹² as evidence for the ferromagnetism of hematite, are clearly instances of ferromagnetism due to the presence of magnetite, as shown by his own chemical analysis: Fe_2O_3 , 93.63 percent; TiO_2 ,

⁸ Alpha hematite is the common form of Fe_2O_3 crystallizing in the rhombohedral system and will hereafter be referred to as hematite. Gamma hematite has the same cubic crystal structure as magnetite, Fe_3O_4 , but has the chemical composition Fe_2O_3 . It is distinctly ferromagnetic but somewhat unstable.

⁹ Jakob Kunz. Neues Jahrbuch für Mineralogie, 1, 1907, p. 62.

¹⁰ J. Koenigsberger, Wied. Ann., 66, 1898, p. 727.

¹¹ Westmann. Dissertation, Upsala, 1896.

¹² International Critical Tables. McGraw-Hill Book Company, 6, 1929, p. 414.

3.55 percent; FeO, 3.26 percent. This amount of FeO corresponds to 10.8 percent Fe₃O₄, and this amount is sufficient to obscure any ferromagnetic influence of hematite. When it is considered that magnetite is 10,000 times as magnetic as hematite, Westmann's data must be excluded as indications of the ferromagnetism of hematite. Similar doubts might be attached to the data of Smith¹³ who made very precise measurements on crystals of hematite. Smith gives no chemical analysis and evidently assumed the crystalline form to be an indication of high purity. It is well known¹⁴ that FeO and Fe₂O₃ form solid solutions which can form perfect crystals. Despite the precision of Smith's measurements, his data were not suitable for the purpose in view because of the wide variation in values which should be characteristic constants of the material.

The wide divergence in the susceptibility¹⁵ of hematite (20×10^{-6} to 5000×10^{-6}) found by numerous investigators has been explained in many ways. Chevalier and Begui¹⁶ ascribe the high susceptibility values to the presence of alkaline impurities as do Herroun

¹³ T. T. Smith. The Magnetic Properties of Hematite. Phys. Rev. 8, 1916, p. 721.

¹⁴ J. W. Greig, H. E. Merwin, E. Posnjak, and R. B. Sosman. Equilibrium Relationships of Fe₃O₄, Fe₂O₃, and O. Amer. Jour. Sci., 30, 1935, pp. 239-316.

¹⁵ Throughout this paper susceptibility shall mean the mass susceptibility X_g , unless otherwise stated.

¹⁶ R. Chevalier and Z. E. Begui. Thermomagnetic Properties of Ferric Oxide. Societe' Chimique, Nov. 1937, pp. 1735-41.

and Wilson¹⁷ and Duparc.¹⁸ Others have explained this as due to the mode of preparation¹⁹ and to naturally occurring ferromagnetic ferric oxide.²⁰ Stoner²¹ concludes that pure Fe_2O_3 is probably not ferromagnetic and believes that a nonferromagnetic sesquioxide can be prepared. This is somewhat of the feeling possessed by some of the French school of mineral physicists even though natural hematites were shown to exhibit such indications of ferromagnetism as a definite Curie point²² independent of the method of preparation of the Fe_2O_3 , and variation of susceptibility with grain size.²³

The first indications that hematite really possesses a high coercive force and might be capable of concentration on an alternating-current separator were noticed by Davis and at about the same time by Sokolovsky.

¹⁷ E. Wilson and E. F. Herroun. Proc. Phys. Soc., 33, 1921, p. 196.

¹⁸ L. Duparc and co-workers. Bull. Soc. Min., 37, 1914, p. 28.

¹⁹ G. F. Huttig and H. Kuttel. Zeit. Anorg. Chem., 199, 1931, p. 129.

²⁰ R. B. Sosman and E. Posnjak. Jour. Wash. Acad., 15, no. 14 (August 1925).

²¹ Edmund C. Stoner. Magnetism and Matter. Methuen and Co., Ltd., London, 1934, p. 529.

²² See footnote 16.

²³ Raymond Chevalier and Mlle. Suzanne Mathew. Variation of the Magnetic Susceptibility of Hematite Powders as a Function of the Size of the Grains. C. R., 204, 1937, pp. 854-6.

Several investigators²⁴ have been interested in applying Mordey's discovery to alternating current magnetic concentration and the Metallurgical Division of the United States Bureau of Mines has done considerable research along these lines.²⁵ C. W. Davis noticed

²⁴ (a) W. M. Mordey. Demonstration of Some Recent Studies in Alternating Magnetism and Some Possible Applications. Proc. Phys. Soc., 40, 1928, p. 338.

(b) J. A. L. Ortlepp. Alternating Current in Magnetic Separation. Jour. Chem. and Met. Soc. of South Africa, 30, 1929, pp. 99-128.

(c) B. W. Holman. Recent Research in Ore Dressing, IV - Magnetic and Hysteretic Separation. South African Min. and Eng. Jour., 36, part 2, 1925, pp. 138-141, 171-173.

(d) H. Stafford Hatfield. The Action of Alternating and Moving Magnetic Fields Upon Particles of Magnetic Substances. Physics, 7, no. 2, 1936, pp. 604-10.

²⁵ (a) R. S. Dean, V. H. Gottschalk, and C. W. Davis. Magnetic Separation of Minerals. Report of Investigations 3223, Bureau of Mines, 1934, pp. 3-13.

(b) C. W. Davis. Alternating Current Magnetic Separation of Iron Ores. Report of Investigations 3229, Bureau of Mines, 1934, pp. 35-37.

(c) R. S. Dean and C. W. Davis. Magnetic Concentration of Ores. Trans. Amer. Inst. Min. and Met. Eng., 112, 1934, pp. 509-537.

(d) V. H. Gottschalk and C. W. Davis. Apparatus for Determining Magnetic Constants of Mineral Powders. Report of Investigation 3268, Bureau of Mines, 1935, pp. 51-67.

(e) C. W. Davis. Magnetic Properties of Mineral Powders and Their Significance. Ibid, pp. 91-101.

(f) C. W. Davis. Practical Aspects of Alternating Current Magnetic Separation. Ibid, pp. 91, 107.

(g) Donald Jay Doan. Effect of Lattice Discontinuities on the Magnetic Properties of Magnetite. Report of Investigation 3400, Bureau of Mines, 1938, pp. 65-86.

that if hematite particles were magnetized in a strong direct current magnetic field and placed on an alternating current separator, they showed a faint hysteretic or repelling action. No quantitative results were obtained at the time because the force of repulsion appeared to be so small that it could not be used for a separation process. Nevertheless, the results showed that hematite had a remanence and a coercive force. In 1935, Sokolovsky²⁶ found the same action and made quantitative tests on the amount of repulsion in various fields and at different frequencies of alternation. In the course of his experiments he reached the same conclusions concerning alternating current magnetic separation as Davis, Dean, and Gottschalk of the Bureau of Mines; namely, that a material must have a high coercive force as well as a high permeability if alternating current magnetic separation is to be feasible. Sokolovsky performed alternating current separations on hematite of high purity (69.60 to 70.05 percent) and found that if hematite was first "activated" by magnetization in a field of 4,000 to 5,000 oersteds, and then placed over an alternating current magnet, a definite repulsion took place, depending on the frequency of alternation and the size of the hematite grains. This shows definitely that hematite is ferromagnetic but Sokolovsky was more concerned with a verification of Ortlepp's²⁷ work on magnetic separation and seemingly recognized nothing new in this property of hematite.

²⁶ G. S. Sokolovsky. Use of Alternating Magnetic Fields for Electromagnetic Enrichment of Ores. *Mechanobr*, 15th Year Jubilee Volume, 1935, pp. 523-542.

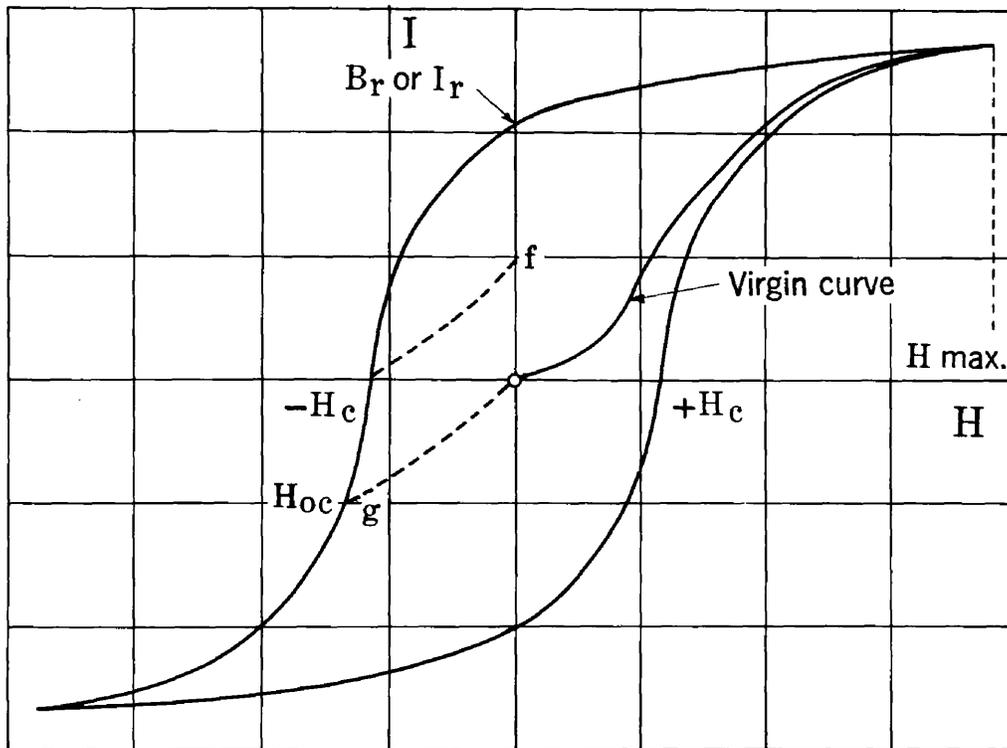
²⁷ See footnote 24b.

Smith's work is the only one found in the literature that quotes any figures for the coercive force and remanence of hematite, but due to the few values given there is little possibility of applying his data to commercial magnetic separation.

GENERAL CONSIDERATIONS

Hysteresis. Hysteresis in magnetism has been studied so extensively during the past century that there is little need to discuss more than the elementary facts of a hysteresis loop. Figure 1 represents a characteristic curve for hysteresis in a typical ferromagnetic material and shows the main points of interest: H_{\max} , the maximum magnetic field used, B_r , the magnetic remanence of the material after magnetization, and H_c , the coercive force, which is the negative field required to reduce the residual magnetism to zero. Although the point H_{oc} is of little interest in ordinary ferromagnetics, it takes on somewhat more importance in this problem. Spooner²⁸ calls this the open-circuit coercive force, by which is meant the reverse magnetizing force necessary to leave the sample in a state of zero magnetization after the magnetizing force has been removed. This value is not a constant of the material but is rather a function of the dimension ratio if the magnetic test is not made in a closed circuit. The true H_c value is that obtained under closed- or open-circuit conditions when the demagnetizing force reduces the remanence to zero while the demagnetizing force is still applied. If the H_c value of magnetizing force is removed, the induction rises to f . The open-circuit coercive force is the value of the demagnetizing field which when removed will cause the induction to rise to zero along $g - o$. Although the H_{oc} is of doubtful value, it will be used later in discussing the demagnetization of hematite.

²⁸ T. Spooner. Properties and Testing of Magnetic Materials. McGraw-Hill Book Co., 1927, pp. 62-65.



M-3
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Figure 1 .—Hysteresis loop of a ferromagnetic substance.

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Nomenclature.

Quantity	:	Symbol	:	Unit
Magnetic induction	:	B	:	Gauss
Remanence	:	B_r	:	Gauss
Magnetic field	:	H	:	Oersted
Maximum magnetic field	:	H_{max}	:	Oersted
Coercive force	:	H_c	:	Oersted
Magnetization density*	:	$4 \pi I$:	Gauss
Volume susceptibility	:	k	:	
Mass susceptibility	:	X_g	:	
Field gradient	:	$\frac{\partial H}{\partial x}$:	

*T. F. Wall. Applied Magnetism, London, E. Benn, Ltd.,
1927, p. 72.

MATERIAL USED

Purity of hematites. The importance of purity of hematite cannot be over-emphasized. Herroun and Wilson²⁹ have aptly summed up the situation as follows:

When it is remembered that one part of carbon can reduce eighty times its own weight of Fe_2O_3 to Fe_3O_4 , and that the susceptibility of magnetite is some ten thousand times greater than that of Fe_2O_3 , the enormous error that can be introduced by traces of organic impurity will be realized; in fact, there is little doubt that the change in susceptibility brought about by heating pure Fe_2O_3 with any substance capable of reducing it would be a more delicate test for, say, organic carbon or hydrogen than any other at present known.

After considering the wide variation in susceptibility of Fe_2O_3 produced by many different chemical processes, one arrives at the conclusion that it is extremely difficult to get pure Fe_2O_3 . Analysis of hematite for gamma Fe_2O_3 content and even for small amounts of Fe_3O_4 is practically impossible. An amount of Fe_3O_4 so small that it cannot be detected chemically is sufficient to cause a large increase in the susceptibility of hematite. Neither spectrographic analysis nor X-ray work can detect the presence of very small amounts, say, less than 0.1 percent, of alpha or gamma Fe_2O_3 in Fe_3O_4 , or vice versa. The question then arises--how do we know that the ferromagnetic properties measured in this work were actually those of hematite? The answer to this will be found in the discussion which shows that the method developed for these measurements is probably the most sensitive means known for determination of magnetic impurities in hematite.

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See footnote 17.

Source and analyses of hematites. Three natural hematites and one lot of artificial Fe_2O_3 were used in this experimental work. The first hematite was one from Cumberland, England, purchased through Ward's Natural Science Establishment, Inc. It was broken down to -6 mesh, using a brass hammer and aluminum plate, ground in a pebble mill for about 6 hours, and then fractionated into various sizes by means of a Roller³⁰ air analyzer. All size fractions were checked microscopically and found to have less than about 3 percent oversize. The chemical analysis for each of the air-analyzed fractions is as follows:

Size in microns	Fe percent	Insol. percent
0 to 5	66.02	3.5
5 to 10	65.1	4.6
10 to 20	65.6	4.7
20 to 40	65.9	4.5
40 to 74	67.2	2.5

These analyses account for about 98-1/2 percent of the materials present if the assumption is made that all iron is present as Fe_2O_3 . An extremely low percentage of the grains in any one fraction were attracted by a magnetized needle observed under the microscope.

Hematite no. 1 was from the Michigan iron range. No chemical analysis was made on this sample but magnetic measurements showed it to be almost free of magnetic impurities. This hematite came in massive

³⁰ P. S. Roller. Separation and Size Distribution of Microscopic Particles--An Air Analyzer for Fine Powders. Report of Investigations 3268, Bureau of Mines, 1935.

lumps remarkably homogeneous and large enough to yield rods $3/8$ inch square and 4 inches long. The measurement on these rods provide welcome corroboration of the assumption that the mass susceptibility is constant regardless of the density. One air fraction and two sieve fractions also were made from the remainder of the ore.

No. 2 hematite had the following analysis:

	<u>Percent</u>
Iron	66.94
Phosphorus	.054
Silica	2.10
Manganese	.16
Alumina	.54

Magnetic measurements indicated the presence of some magnetic impurity in amounts sufficient to cause abnormal susceptibilities.

The artificial Fe_2O_3 was Baker's Analyzed Ferric Oxide, Powdered, Lot no. 4137.

Preliminary measurements were made on the Nagaunee, Michigan, hematite, which since the investigations of Cooke³¹ has been used frequently as a typical American iron ore. This material was not considered in the final definitive measurements because it contained too much magnetite or gamma hematite.

³¹ S. R. B. Cooke. Microscopic Structure and Concentratibility of American Iron Ores. Bulletin 331, Bureau of Mines, 1936.

THEORY

Fundamental equations. The methods generally used for measuring ferromagnetic substances are not suited for use on hematite because the effects are so small that they would be masked by instrumental errors; therefore, another method was used which depends on the force K exerted by a nonhomogeneous field on a test body. This is not new and although it has been discussed in many textbooks a review of the two principal methods will be given here because both were used in this work. Much of what follows is patterned after the excellent presentation given by Klemm.³²

The force K which acts on a body of magnetic moment M in a nonhomogeneous field $\frac{\partial H}{\partial x}$ is given by the equation³³

$$1. \quad K = M \frac{\partial H}{\partial x}$$

A body of susceptibility k takes on the moment kH per cm^3 in a field H and, for a small volume, equation 1 becomes

$$2. \quad dK = kH \frac{\partial H}{\partial x} dv$$

Strictly speaking, this equation is derived for a body of constant susceptibility whose magnetic moment is generated by the external field and for that reason some of the results presented herein are open to the criticism that the susceptibility values are not ideal susceptibilities. Bitter³⁴ explains this difference between reversible

³² Wilhelm Klemm. *Magnetochemie*, Akademische Verlagsgesellschaft M.B.H., Leipzig, 1936.

³³ This equation is derived by taking moments of a body in a magnetic field.

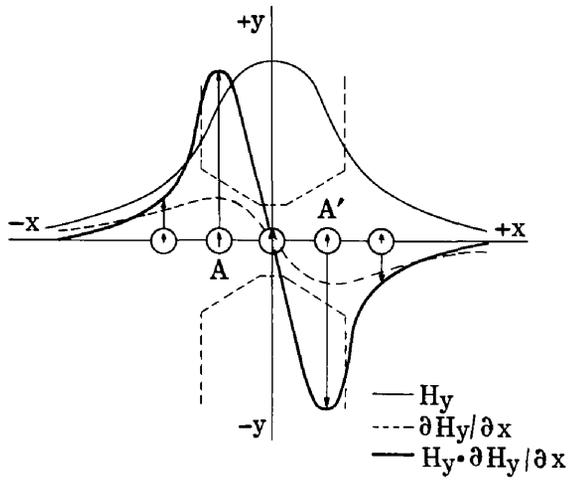
³⁴ Francis Bitter. *Introduction to Ferromagnetism*. McGraw-Hill Book Co., New York, 1937, p. 181.

susceptibility and true para- or diamagnetic susceptibility as a hysteresis phenomenon. The errors introduced in this work by the use of equation 2 are small due to the fact that the reversible susceptibility differs very little from the ideal for even large increases in H because the susceptibility values for hematite are of the same magnitude as a strongly paramagnetic substance. In a true ferromagnetic the value of k is a complex function of H at low fields, but in the neighborhood of saturation k is constant. In a broader sense, the whole basis for the experimental method used is the fact that hematite has an irreversible susceptibility.

Methods of susceptibility measurements based on equation 2 may be divided into two distinct classes: (1) The test body is so small that $H \frac{\partial H}{\partial x}$ may be considered constant and the differential equation 2 can be used directly, and (2) the test body becomes so large that (2) must be integrated:

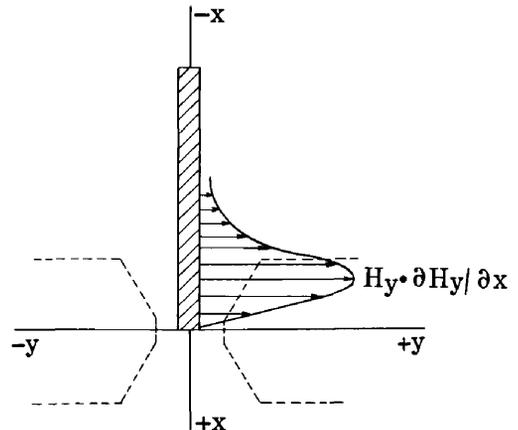
$$K = k \int H \frac{\partial H}{\partial x} dv$$

Measurements based on the differential equation. The quantities H , $\frac{\partial H}{\partial x}$ and $H \frac{\partial H}{\partial x}$ for a normal electromagnet will be considered first. In figure 2A the lines of force proceed along ϕ from the north pole to the south pole. Consider a small paramagnetic body placed in the field at points indicated by the circles. The induced moments are indicated by the small arrows within the circles while the forces acting on the body due to the product $H \frac{\partial H}{\partial x}$ along the x axis are shown by the larger arrows. The forces here considered act along the positive values of x, that is, perpendicular to the direction of the induced moments.



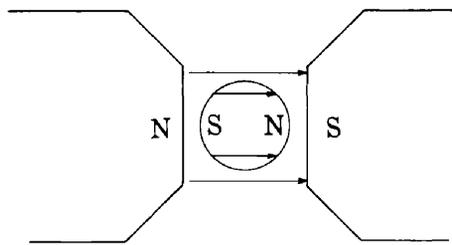
Forces in the nonhomogeneous field of an electromagnet.

A



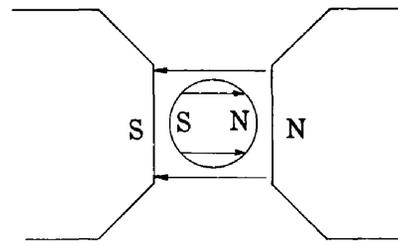
Forces involved in the Gouy method.

B



Normal magnetization of a ferromagnetic in Gouy method.

C



Test body magnetized normally; $-H < H_c$.

D

Figure 2

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The direction of the force exerted by the field on paramagnetic and ferromagnetic bodies is always toward the midpoint of the field, for it is determined by the sign of $\frac{\partial H}{\partial x}$. This differential coefficient is positive on the left side and hence the force proportional to $H \frac{\partial H}{\partial x}$ acts in the direction of increasing values of x , that is, into the field. Even though $H \frac{\partial H}{\partial x}$ is negative on the right side (figure 2A), there is a repulsion in the direction of positive values of x and there is still attraction toward the center of the field.

Measurements based on the differential equation are generally relative. In other words, the force exerted on a test body in a definite portion of the field is compared with the force exerted on a body of known susceptibility placed in exactly the same position. This was the general method used by a number of experimenters.³⁵

Extreme care must be used in this method always to bring the test body to the same position in the field that the known body occupied. This difficulty has largely been overcome by making the form of the pole faces such that $H \frac{\partial H}{\partial x}$ is a constant. This arrangement has been described by Fereday³⁶ and more recently by Rogers and Stamm.³⁷

³⁵ (a) M. Faraday. *Experimental Researches*. Taylor and Francis, London, 3, 1855, pp. 27, 497.

(b) P. Curie. *Magnetic Properties of Substances at Various Temperatures*. *Ann. de Chim. et Phys.*, 5, 1895, p. 289.

(c) C. Cheneveau. *Phil. Mag.*, 20, 1910, p. 357.

(d) G. Foëx. *Researches on Paramagnetism*. *Ann. de Phys.*, 16, 1921, p. 174.

³⁶ R. A. Fereday. *Proc. Phys. Soc. (London)*, 44, 1932, p. 274.

³⁷ B. A. Rogers and K. O. Stamm. *An Apparatus for Determining Thermo-magnetic Behavior of Slags, and Some Preliminary Results Obtained with It*. *A.I.M.M.E., Metals Technology*, T. P. 1133, December 1939.

The apparatus developed by Rogers and Stamm was used for the portion of this work on the thermomagnetic properties of hematite and found to be satisfactory.

Methods of measurement depending on the integrated equation.

Methods using a cylindrical test body³⁸ extending a considerable distance along the X axis (figure 2B) are of greater importance than those using a small spot of the nonhomogeneous field. If $A dx$ is substituted for dv where A is the cross-sectional area of the sample, the force acting in vacuum in the direction of the X axis becomes

$$3. K = A k \int_{x_2}^{x_1} H \frac{\partial H}{\partial x} dx = A k \int_{H_2}^{H_1} H dH$$

$$4. K = 1/2 A k (H_1^2 - H_2^2)$$

where H_1 and H_2 are the values of H at x_1 and x_2 . In this work the position and length of the test sample were chosen such that H_2^2 was negligible in comparison with H_1^2 , and 4 becomes

$$5. K = 1/2 A H_{\max}^2$$

and thus we have an integration of the forces acting all along the tube.

Transposing 5

$$6. k = \frac{2K}{A H^2}$$

$$X_g = \text{mass susceptibility} = \frac{k}{\text{density}} = \frac{k}{\text{grams/cc}}$$

$$7. X_g = \frac{2K \times \text{vol. filling}}{\text{original weight of material} \times A \times H^2}$$

³⁸ This is generally called the method of L. G. Gouy. C. R. Acad. Sci., Paris, 109, 1889, p. 935, but was first given in principle by J. Plücker, Pogg. Ann., 91, 1854, p. 1.

$$8. \quad X_g = \frac{2 \times \text{gain in weight} \times 980 \times \text{vol. filling}}{A = H^2 \times \text{original weight of sample}}$$

$$\frac{\text{volume of filling}}{A} = \text{height of filling}$$

also 1000 mg. = 1 gram

$$9. \quad X_g = \frac{2 \times \text{gain in weight in mg.} \times \text{height of filling}}{H^2 \times \text{orig. wt.} \times 1.019}$$

Equation 9 is the form used for computing most of the experimental data given below.

EXPERIMENTAL

Apparatus. The Gouy-type magnetic balance used for susceptibility determinations is shown in figure 3. It consists essentially of a chemical balance placed on a stand covering an electromagnet, a sample holder, and a device for preventing friction between the sample tube and the magnet pole faces.

The chemical balance was of the type commonly used in quantitative chemical analysis. The left-hand pan was removed, two holes drilled in the balance case directly beneath the hanger arm and a piece of magnetically inert brass welding rod passed through the case to serve as a suspension for the sample holder. All balance parts were nonmagnetic.

The sample holder was a brass tube 5 inches in length and 0.25 inch internal diameter. The tube was magnetically inert within the precision of measurement over the range of field strengths from 500 to 10,000 oersteds. It was suspended from the brass rod by means of a copper wire.

The Gouy balance is so well known that no further description is necessary. It is not suited for measurements involving strongly ferromagnetic materials because of the attraction of the sample to the pole faces. This adherence of the sample to the pole face was evident for a weak ferromagnetic like hematite in fields above 2,000 oersteds. Of the various methods tried for preventing error due to this effect, the most satisfactory was the vibration of two tightly stretched wires parallel to the pole faces.³⁹ When a small alternating current passes

³⁹ S. S. Schaffer and N. W. Taylor. Effect of Complex Ion Formation Upon the Magnetic Susceptibility of Paramagnetic Salts in Aqueous Solution. Jour. Amer. Chem. Soc., 48, 1926, p. 843.

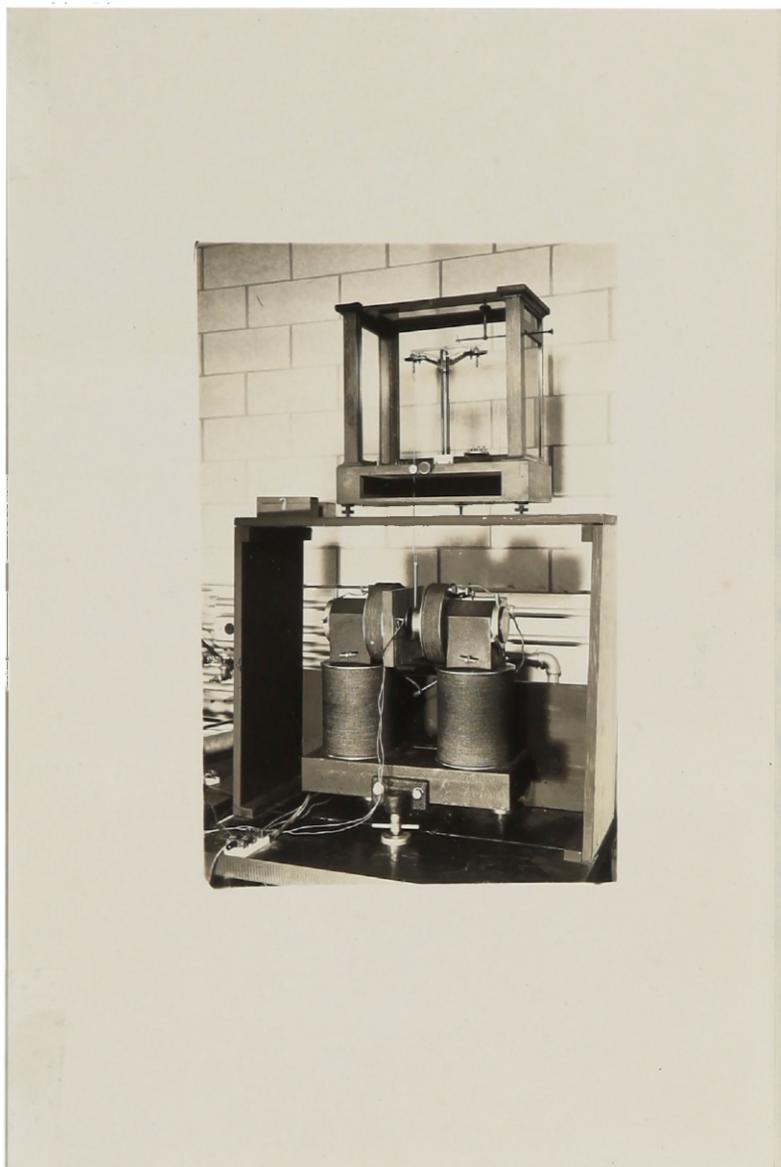


Figure 3. - Gouy-type magnetic balance

through such wires stretched in a magnetic field, they vibrate with the frequency of the alternating current if the correct tension is applied to the wires. The proper tension may be computed from the following considerations: The exact fundamental frequency of a stretched string is given by

$$n = \frac{1}{2L} \sqrt{\frac{T}{m}}$$

n = frequency

L = length

T = tension

m = mass per unit length

This permits the calculation of the exact tension necessary when the fundamental frequency is known. In this case 60 cycle alternating current was used and the tension on the wire adjusted for maximum attraction of the current-carrying conductor. The amplitude of the vibration was so small that it did not interfere with the balance weighings, and the friction of the tube on the pole face was reduced to a minimum during the course of the measurements. This device made it possible to extend the use of the Gouy balance to fields far beyond those possible otherwise.

The magnet was an electromagnet of the Cenco type. It had almost the maximum number of ampere turns permissible without resort to water cooling. The pole pieces were low-carbon content soft iron, threaded on one end so that the air gap could be adjusted to any desired width. It was found most convenient to use the flat pole faces rather than the conical ones available. The pole faces used were 8 centimeters in diameter and the air gap was approximately 1.25 centimeters. At 11 amperes a field strength of almost 10,000 oersteds was attained in the air gap. A calibration curve for these conditions is shown in figure 4.

Slide wire resistances controlled the current supplied and a double-scale ammeter was used to measure the current. A reversing switch was provided for reversing the direction of magnetization across the air gap.

The Curie-type balance used for a small portion of this work to obtain thermomagnetic data was that designed and built by Rogers and Stamm⁴⁰ for measurements on slags at the Pittsburgh Station of the U. S. Bureau of Mines. The main feature of their modification of Curie's apparatus is the use of a special-type pole face properly shaped to make the product $H \frac{\partial H}{\partial x}$ a constant. The temperature in a small furnace inserted between the pole faces could be controlled very accurately.

A Grassot fluxmeter, supplied by the Central Scientific Co., was used as a check for field strength determinations. The current generated by withdrawing a search coil of known area turns from the center of the magnetic field was measured in terms of maxwells by the fluxmeter. The search coils were calibrated by comparison with standard coils of known area turns at the National Bureau of Standards, Washington, D. C.

Calibration. The field strength appears in formula 9 as the square and hence must be determined with accuracy greater than suffices for the other variables. The method finally used was that of comparison with a standard. The gain in weight of a paramagnetic substance of known susceptibility in various fields was found and then substituted in the equation

$$X_g = \frac{2 \times \text{length} \times \text{gain in weight}}{\text{original weight} \times H^2 \times 1.019}$$

⁴⁰ See footnote 37.

Values of H were calculated and plotted against the current producing the field. This method has been extensively used by the French school of physicists and others using the Curie-Cheneveau type balance for investigation of para- and diamagnetic substances.

Stoner⁴¹ states:

Any method of measuring susceptibility involving the use of a homogeneous field may be inversely employed for the determination of unknown fields using substances of known susceptibility.

Satisfactory standards having a higher susceptibility than water are very desirable. Manganese pyrophosphate, $Mn_2P_2O_7$, has been used for this purpose, the susceptibility of a specimen carefully prepared at Strasbourg having been found to remain invariable ($\chi_g = 103.1 \times 10^{-6}$) over a period of years; but the susceptibilities of specimens prepared in different ways may differ by as much as 2 percent. With paramagnetic standards it is, of course, essential to take into account the variation of susceptibility with temperature.

Manganese pyrophosphate was selected as a standard because of its high susceptibility, nonhygroscopic properties, and ease of handling in a powder form. Apparently there is no satisfactory explanation of the variation of the susceptibility with the method of preparation. It is probable that careful study of methods of preparing manganese pyrophosphate would lead to specifications for obtaining a reproducible standard.

The $Mn_2P_2O_7$ was prepared in two ways: The first lot was made according to directions as given by Treadwell and Hall.⁴²

To the slightly acid solution containing Mn equivalent to not more than 0.5 gram $Mn_2P_2O_7$ in 250 ml., and no other metals except alkalies, add 20 g. HCl, 5 to 10 ml. of cold saturated solution of sodium phosphate, and NH_4OH , drop by drop until a slight excess is present. Heat the solution to boiling and keep at this temperature for

⁴¹ E. C. Stoner. Magnetism and Matter. Methuen and Co., Ltd., London, 1934, p. 65.

⁴² E. P. Treadwell and W. T. Hall, Anal. Chem., II, 1928, p. 133.

three or four minutes, or until the precipitate assumes a silky crystalline appearance. After cooling filter the precipitate into a Gooch or Munroe crucible, wash with cold NH_4NO_3 solution, dry, ignite within a larger crucible or in an electric furnace. Cool in a dessicator and weigh as $\text{Mn}_2\text{P}_2\text{O}_7$.

In drying to constant weight a great decrease in volume took place but no loss in weight after 1 hour at about 800°C . in an electric muffle.

The objection to the above method is the oxidation of the manganous salt to the manganic by air in the presence of NH_3 as shown by the brown discolorations found in the product. Another lot of $\text{Mn}_2\text{P}_2\text{O}_7$ was therefore prepared by a different procedure. Aqueous solutions of sodium pyrophosphate and manganese sulfate were prepared, mixed, and $\text{Mn}_2\text{P}_2\text{O}_7$ precipitated. The $\text{Mn}_2\text{P}_2\text{O}_7$ was filtered in a Gooch crucible, washed, dried, and sintered at 700 to 800°C . for 1 hour.

Morris Slavin, Nonmetallics Division, Bureau of Mines, College Park, Md., was kind enough to run the qualitative spectroscopic analysis shown in the following table.

TABLE I
Impurities in Lot 2, $\text{Mn}_2\text{P}_2\text{O}_7$

	Percent
Co, Ni, Ti, and V	0.01 to 0.001
Zr, Sn	.001
Mg, Al	.01 to .10
Na	.50 to 1.0
Fe	.01

The analysis shows that the precipitate was not washed free of Na_2SO_4 . Since the main effect of Na_2SO_4 would be to dilute the $\text{Mn}_2\text{P}_2\text{O}_7$, a susceptibility value of $102 (11) \times 10^{-6}$ was used in all calibration work.

The difference in susceptibility of the $\text{Mn}_2\text{P}_2\text{O}_7$ prepared by the two methods was less than the experimental errors of procedure. This is further support for the expectation that chemical studies might lead to a method for the preparation of standard $\text{Mn}_2\text{P}_2\text{O}_7$ of constant and reproducible susceptibility. There is an urgent need for an international standard of high susceptibility and it is to be hoped that someone will undertake such a study in the near future.

The ampere-field strength curve obtained by comparison with the $\text{Mn}_2\text{P}_2\text{O}_7$ showed variations of less than 1 percent from the curve found by search coil and fluxmeter measurements. The susceptibility of some common paramagnetic substances was then determined with the following results:

TABLE II

Comparison of experimental and International
Critical Tables values for some common salts
(Aqueous solution)

Substance	Experimental value $X_g \times 10^6$	I. C. T. value $X_g \times 10^6$	Percent difference
MnSO_4	88.2	88.0	+0.2
NiCl_2	44.7	45.1	-.9
NiSO_4	26.7	26.9	-.8

All evidence thus indicates that field strength measurements were accurate to 1 percent. The variation of magnetic impurities in hematite and differences in packing the sample tube exceed this accuracy two to three times.

The air gap had a higher flux density on going from strong to weak fields and it was necessary to calibrate the magnet for both increasing and decreasing current strengths. This is undoubtedly due to the ferromagnetic nature of the pole pieces.

The magnet of the Curie balance was calibrated in the usual fashion with search coil and ballistic galvanometer. Rogers and Stamm's apparatus as originally developed gave only relative susceptibility values. Since their last publication a change in method of sample attachment has greatly facilitated measurements and work already has been done on changing relative to absolute values. In this work on hematite the pull on a known mass of $Mn_2P_2O_7$ in a known field was measured and unknowns compared with it by means of the relationship:

$$X_g = \frac{102 \times 10^{-6} \times m_2 \times K_2}{m_1 \times K_1}$$

Where X_g = susceptibility of unknown

102×10^{-6} = susceptibility of $Mn_2P_2O_7$

m_1 = mass of $Mn_2P_2O_7$

m_2 = mass of unknown

K_1 = force to balance known

K_2 = force to balance unknown

Unfortunately, the balance was not sensitive below 10 milliamperes balancing current. The thermomagnetic data should be taken then as indicative rather than absolute.

Procedure. The use of the Gouy-type magnetic balance was extended to obtain susceptibilities over a large range of field strengths and so permit the plotting of a hysteresis curve from the data so obtained. Usually measurements with the Gouy- or Curie-type balance operate at only one fixed field strength.

It was noticed that when the sample of hematite was turned 180° perpendicular to the direction of pull after magnetization, the material weighed less than the original sample. Figures 2C and 2D show the direction of magnetization in each case. Figure 2C represents the condition of magnetization in the second quadrant of a hysteresis loop. When the applied force becomes large enough to reduce the magnetization in the sample to zero, there is no longer a repelling force as in figure 2D, or an attracting force as in figure 2C, but a condition of zero magnetization exists. The field applied in the direction opposite to that of magnetization which reduces the remanence to zero is known as the coercive force.

The procedure finally developed for determining the hysteresis loop of hematite by means of a continuous and uninterrupted series of susceptibility measurements was quite different from the usual methods of finding the magnetic properties of materials. The following steps show how the data were obtained:

1. The brass sample tube was filled with hematite powder. The powder was tamped to give the same length of sample in every case.
2. The tube was then suspended from the brass welding rod and the weight of the sample tube and contents balanced exactly by the use of a tare.

3. The direct current power for the magnet was then applied and adjusted by means of the variable resistances for the minimum field strength to be used.

4. The alternating current was adjusted for minimum vibration of the spacer wires.

5. The gain in weight of the material in the magnetic field was then found by adding weights to the pan until a balance was reached.

6. Without interrupting the flow of direct current even momentarily the field strength was increased by steps of about 1,000 oerstedes and balance weights for each step recorded until the maximum field strength was reached.

7. After reaching the strongest field, the current was decreased by small steps and weighings made in the direction of strong to weak fields. The magnet was not turned off from the time the virgin curve was determined until the H_c was found.

8. After weighing in the weakest field the current was reduced to zero and the polarity of the magnet reversed by means of a reversing switch.

9. The field strength was then increased (now in reverse direction to the original magnetizing force) until the material showed a zero gain in weight. At this point $k H = 0$ and, therefore, this was the opposing field which reduced the remanence to zero. By definition this is the coercive force H_c .

10. Field strengths were increased once more and weighings made up to the maximum field used. Steps 7, 8, and 9 were repeated

to obtain data for the lower side of the hysteresis loop (third, fourth, and first quadrants).

11. The tube was then emptied and the contents weighed.

Limitation of the procedure. It is interesting to note that very few materials can be analyzed magnetically in this fashion. If the susceptibility becomes of the order of 2×10^{-4} in field strengths above 3,000 or 4,000 oersteds, the side attraction of the magnet faces becomes too great to be counteracted by the weak force of the vibrating wires. Also in a material with a high remanence the turning torque of the magnetized material becomes quite high and the sample tube must be rigidly attached to the rod suspended from the balance arm. The torque was low for hematite and a suspension of no. 16 copper wire kept the tube from turning. As the field strengths increase, the balance point becomes harder to find and, consequently, there is about the same precision of measurement at high and low fields.

Computation. A detailed calculation of one value of χ is here-with presented.

Data:

Ammeter reading	2.00 amperes
Gain in weight	355 mg.
Sample weight	7.03 g.
Length of sample	11.7 cm.
Density of sample	2.15 gms./cm ³

An ammeter reading of 2.00 amperes indicates a field strength of 5,340 oersteds (figure 4).

Solving for X_g :

$$X_g = \frac{2 \times \text{length} \times \text{gain in weight}}{\text{original weight of material} \times H^2 \times 1.019}$$

$$= \frac{2 \times 11.7 \times 355}{7.03 \times (5340)^2 \times 1.019}$$

$$X_g = 40.7 \times 10^{-6}$$

Volume susceptibility (k) = X_g x apparent density

$$k = 40.7 \times 2.15 = 87.4$$

$$4 \pi k H = 4 \pi I$$

$$4 \pi I = 12.57 \times 87.4 \times 5340 = 5.88 \text{ gaussess.}$$

A hysteresis loop can then be drawn by plotting a series of $4 \pi I$ values against the corresponding values of H .

Coercive force values are obtained directly from the experimental data whereas B_r values must be interpolated from the hysteresis loops.

Results. Tables III to IX, inclusive, contain the susceptibility data for Cumberland hematite; table X that for C. P. Ferric Oxide; XI to XIV, inclusive, the data for Michigan hematite no. 1, and similar material for Michigan hematite no. 2 is shown in table XV.

In most cases the lower half of the hysteresis loop was drawn by symmetry.

No points are shown in the second quadrant of the hysteresis loops for the reason that it was found time-consuming to obtain necessary data for such points. Such a procedure is perfectly valid since the H_c and B_r values are independent of the shape of the curve in the second quadrant.

Tables XVI and XVII summarize most of the H_c and B_r data found in tables III to XV, inclusive.

Tables XVIII and XIX contain results obtained on the Curie-type balance.

Figure 5 is a graphical representation of the results in table III, figure 6 that of table IV, and figure 7 that of table VII.

Figure 8 presents the results of table XII. Figure 9 shows change in susceptibility and H_c as H changes. Figures 10 and 11 show graphically the H_c and B_r data given in table XVI and XVII.

The curves in figure 10 should be considered as indicative of the probable change of H_c with particle size. Such research was really not pertinent to the problem and the labor involved in preparing numerous, carefully sized fractions in order to obtain absolute results was not justified.

Figure 12 shows the change in susceptibility of a hematite as it is heated and then cooled in a magnetic field. Figure 13 contains hysteresis curves before and after heating the same hematite.

TABLE III

Susceptibility data for Cumberland hematite

Size 0-5 microns
 Weight 3.537 grams
 Length 11.7 cm.
 Density 1.13 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
610	.377	4	69.0	.60
1310	1.72	20	75.6	1.51
2040	4.16	48	75.0	2.18
3390	11.5	131	74.0	3.56
5410	29.3	333	73.9	5.67
6910	47.8	458	63.7	6.25
8000	64.0	603	61.2	6.96
6910	47.8	498	67.7	6.64
5410	29.3	353	78.3	6.01
3390	11.5	193	109	5.25
2090	4.16	100	156	4.51
1310	1.72	57	215	4.00
614	.377	23	397	3.47
Reverse				
2235		0	0	0
3390	11.5	67	37.9	1.82
5410	29.3	258	57.2	4.40
6910	47.8	453	61.7	6.05
8000	64.0	583	59.2	6.73
6910	47.8	503	67.8	6.68
5410	29.3	350	78.2	5.98
3390	11.5	193	109	5.25
2040	4.16	102	159	4.57
1310	1.72	56	210	3.95
614	.377	23	397	3.47
Reverse				
2235		0	0	0
3390	11.5	65	37.5	1.78
5410	29.3	266	58.7	4.51
6910	47.8	441	61.6	6.01
8000	64.0	603	61.2	6.96

TABLE IV

Susceptibility data for Cumberland hematite

	Size	0-5	microns	
	Weight	7.307	grams	
	Length	11.7	cm.	
	Density	2.30	gms./cm ³	
H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	4 VI
614	.377	8	66.3	1.23
1310	1.72	40	73.0	2.82
2040	4.16	93	71.4	4.21
3390	11.5	261	71.4	7.06
5410	29.3	643	69.1	10.8
6910	47.8	983	64.8	12.9
8000	64.0	1258	61.9	14.3
6910	47.8	1048	69.1	13.8
5410	29.3	733	78.7	12.3
3390	11.5	409	112	11.0
2040	4.16	207	148	8.72
1310	1.72	119	218	8.34
614	.377	49	409	7.30
Reverse				
2235		0	0	0
3390	11.5	140	38.3	3.75
5410	29.3	527	56.6	8.84
6910	47.8	910	60.0	12.0
8000	64.0	1238	60.9	14.1
6910	47.8	1035	68.8	13.6
5410	29.3	720	78.4	12.1
3390	11.5	401	108	10.9
2040	4.16	205	143	8.67
1310	1.72	117	213	8.05
614	.377	48	400	7.17

TABLE V

Susceptibility data for Cumberland hematite

Size 5-10 microns
 Weight 4.063 grams
 Length 11.7 cm.
 Density 1.28 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
614	.377	21	365	3.11
1310	1.72	184	286	6.03
2040	4.16	168	229	7.51
3390	11.5	393	193	10.5
5410	29.3	792	153	13.2
6910	47.8	1141	135	15.0
8000	64.0	1417	125	16.1
6910	47.8	1202	143	15.9
5410	29.3	847	169	14.3
3390	11.5	453	223	12.1
2040	4.16	231	314	10.3
1310	1.72	132	434	9.2
614	.377	45	683	6.7
Reverse				
580		0	0	0
1310	1.72	43	142	3.00
2040	4.16	124	169	5.53
3390	11.5	338	166	9.03
5410	29.3	707	136	11.8
6910	47.8	1037	123	13.6
8000	64.0	1347	119	15.3
6910	47.8	1142	135	15.0
5410	29.3	797	154	13.4
3390	11.5	414	204	11.1
2040	4.16	221	300	9.84
1310	1.72	124	408	8.60
614	.377	40	616	6.08
Reverse				
580		0	0	0
1310	1.72	60	197	4.15
2040	4.16	138	188	6.18
3390	11.5	364	179	9.76
5410	29.3	775	149	13.0

Susceptibility data for Cumberland hematite

Size 10-20 microns
 Weight 8.751 grams
 Length 11.7 cm.
 Density 2.76 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
614	.377	13	90.6	1.93
1310	1.72	65	99.4	4.51
2040	4.16	143	88.0	6.21
1310	1.72	71	108	4.92
614	.377	22	153	3.26
Reverse				
200		0	0	0
614	.377	11	80.1	1.70
1310	1.72	55	84.0	3.80
2040	4.16	136	85.9	6.08
Reverse				
3390	11.5	360	82.3	9.72
5410	29.3	903	81.0	15.2
3390	11.5	469	107	12.6
2040	4.16	234	148	10.5
1310	1.72	124	189	8.67
614	.377	42	293	6.22
Reverse				
1250		0	0	0
2040	4.16	87	55.0	3.94
3390	11.5	351	80.2	9.40
5410	29.3	909	81.5	15.3
Reverse				
6910	47.8	1469	80.8	19.4
8000	64.0	1829	75.1	20.8
6910	47.8	1484	81.7	19.5
5410	29.3	1029	92.3	18.7
3390	11.5	526	120	14.1
2040	4.16	263	166	11.7
1310	1.72	149	228	10.3
614	.377	55	383	8.11
Reverse				
1630		0	0	0
2040	4.16	64	40.4	2.84
3390	11.5	283	64.7	7.62
5410	29.3	830	74.4	13.9
6910	47.8	1369	75.3	18.0
8000	64.0	1799	73.9	20.5

TABLE VII

Susceptibility data for Cumberland hematite

	Size	20-40	microns	
	Weight	9.929	grams	
	Length	11.7	cm.	
	Density	3.13	gms./cm ³	
H	$H^2 \times 10^{-6}$	Gain (mg)	$X_g \times 10^6$	$4 \pi I$
614	.377	13	81.2	1.96
1310	1.72	66	88.8	4.58
2040	4.16	154	85.5	6.85
3390	11.5	434	87.4	11.6
5410	29.3	1066	84.5	18.0
6910	47.8	1556	75.4	20.5
8000	64.0	1991	72.0	22.6
6910	47.8	1611	78.1	21.2
5410	29.3	1131	89.4	19.0
3390	11.5	595	120	16.2
2040	4.16	308	171	13.7
1310	1.72	171	230	11.8
614	.377	64	393	9.5
Reverse				
1560		0	0	0
2040	4.16	48	26.7	2.14
3390	11.5	307	61.8	8.22
5410	29.3	951	75.1	16.0
6910	48.7	1411	68.4	18.6
8000	64.0	1881	68.0	21.4
6910	48.7	1501	72.8	19.8
5410	29.3	1101	87.0	18.5
3390	11.5	566	114	15.2
2040	4.16	288	161	12.9
1310	1.72	161	217	11.2
614	.377	61	375	9.05
Reverse				
1560		0	0	0
2040	4.16	73	40.6	3.26
3390	11.5	358	72.1	9.60
5410	29.3	988	78.1	16.6
6910	48.7	1541	74.7	20.3
8000	64.0	1991	72.0	22.6

TABLE VIII

Susceptibility data for Cumberland hematite

Size 40-74 microns
 Weight 11.191 grams
 Length 11.7 cm.
 Density 3.52 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
644	.415	12	59.4	3.54
1330	1.76	53	61.8	3.64
2050	4.20	139	68.1	6.17
3440	11.8	420	73.2	11.1
5320	28.3	1095	79.4	18.7
6940	48.2	1699	72.6	22.3
7920	62.7	2103	68.8	24.1
6940	48.2	1790	76.4	23.4
5320	28.3	1253	91.0	21.4
3440	11.8	651	113	17.2
2050	4.20	330	161	14.6
1330	1.76	190	218	12.8
644	.415	76	363	10.3
Reverse				
1300		0	0	0
2050	4.20	39	19.1	2.74
3440	11.8	347	60.4	9.20
5320	28.3	984	71.5	16.8
6940	48.2	1539	68.5	21.0
7920	62.7	2019	66.2	23.2
6940	48.2	1619	69.0	21.2
5320	28.3	1174	85.2	20.0
3440	11.8	633	110	16.8
2050	4.20	309	151	13.1
1330	1.76	175	203	11.9
644	.415	69	341	9.72
Reverse				
1300		0	0	0

TABLE IX

Susceptibility data for Cumberland hematite

Size 591-1652 microns
 Weight 11.553 grams
 Length 11.7 cm.
 Density 3.64 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
644	.415	12	57.5	1.68
2090	4.37	120	54.8	5.24
5420	29.3	977	66.2	16.4
8170	66.9	2017	60.0	22.4
5420	29.3	1115	75.6	18.7
2090	4.37	323	147	12.7
644	.415	73	350	10.3
Reverse				
1200		0	0	0
3440	11.8	217	36.6	5.82
5420	29.3	801	54.4	13.7
8170	66.9	1967	58.4	21.7
5420	29.3	1007	68.3	16.9
3440	11.8	513	86.3	13.5
2090	4.37	274	125	10.8
644	.415	72	341	10.4
Reverse				
1200		0	0	0
3440	11.8	307	52.8	8.33
5420	29.3	907	61.4	15.7
8170	66.9	1977	59.0	22.3

TABLE X

Susceptibility data for C.P. ferric oxide

Precipitated Fe_2O_3
 Weight 3.096 grams
 Length 11.7 cm.
 Density .975 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
357	.127	1	58.5	.256
984	.968	10	76.0	.917
1670	2.80	30	79.4	1.63
2425	5.88	64	80.9	2.41
3210	10.3	110	79.3	3.12
5220	27.3	274	74.7	4.78
6385	40.8	364	66.7	5.22
6952	48.3	424	65.2	5.56
7500	56.3	489	64.5	5.93
8150	66.4	534	59.7	5.96
8794	77.3	615	62.0	6.68
9484	89.9	705	58.3	6.78
8880	78.6	639	60.4	6.67
8110	65.8	555	62.7	6.23
7630	58.2	515	65.7	6.15
7080	50.1	458	67.9	5.89
6510	42.4	406	71.2	5.68
5270	27.8	317	84.7	5.47
3490	12.2	174	129	5.52
2690	7.24	120	123	4.06
1940	3.76	78	154	3.66
1270	1.61	46	212	3.30
525	.276	17	458	2.95
Reverse				
2010		0	0	0
2380	5.66	27	35.4	1.03
3320	11.0	80	54.0	2.19
5500	30.3	264	64.8	4.50
6410	41.1	337	60.9	4.79
7130	50.8	408	59.6	5.21
7740	59.9	483	59.9	5.68
8210	67.4	517	56.6	5.70
8950	80.1	624	57.9	6.35
9480	89.9	705	58.3	6.78

TABLE XI

Susceptibility and H_c data for Michigan hematite no. 1

Size 0-5 microns
 Weight 7.03 grams
 Length 11.7 cm.
 Density 2.15 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
575	.330	5	49.5	.770
910	.825	13	51.5	1.23
1230	1.52	25	53.8	1.79
2990	8.97	127	46.3	3.75
4150	17.2	227	43.2	4.85
5340	28.5	355	40.7	5.88
6550	42.8	510	38.9	6.92
7180	51.4	615	34.2	7.65
8670	75.0	850	37.0	8.70
9880	97.5	1070	35.9	9.62
8680	75.1	880	38.3	9.05
7260	52.8	700	43.3	8.55
6580	43.2	610	45.5	8.13
5560	30.8	475	50.3	7.53
4320	18.6	355	62.3	7.28
3200	10.2	207	66.5	5.77
2310	5.33	138	84.5	5.28
1610	2.59	87	110	4.80
910	.825	42	167	3.95
Reverse				
2340		0	0	0
2990	8.97	38	13.9	1.13
4150	17.2	142	27.0	3.03
5340	28.5	345	29.4	5.72
6500	42.2	470	33.4	6.42
7180	51.4	565	36.0	7.04
8670	75.0	830	36.0	8.50
9810	96.1	1060	36.2	9.68

TABLE XII

Susceptibility and H_c data for Michigan hematite no. 1

Size 40 + 100 mesh
 Weight 10.8 grams
 Length 11.7 cm.
 Density 2.91 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
575	.330	11	72.8	1.70
1230	1.52	55	76.9	3.46
1960	3.85	144	79.5	5.72
2990	8.97	326	77.5	8.45
4150	17.2	625	77.4	11.75
5340	28.5	940	70.7	13.8
6550	42.8	1235	61.4	14.7
7180	51.4	1440	59.7	15.7
8670	75.0	1890	53.7	17.0
9850	96.9	2300	50.6	18.3
8680	75.1	1990	56.4	17.9
7260	52.8	1565	63.2	16.7
6580	43.2	1360	67.1	16.1
5560	30.8	1085	75.0	15.2
4320	18.6	835	95.6	15.1
3200	10.2	583	122	14.3
2310	5.33	380	152	12.8
1610	2.59	253	208	12.3
910	.825	122	315	10.5
Reverse				
2340		0	0	0
2990	8.97	108	25.7	2.81
4150	17.2	380	47.0	7.15
5340	28.5	705	52.6	10.3
6550	42.8	1140	56.7	13.6
7180	51.4	1420	59.0	15.6
8670	75.0	1850	52.6	16.6
9850	96.9	2300	50.6	18.3

TABLE XIII

Susceptibility and H_c data for Michigan hematite no. 1

Weight 25.4 grams
 Size $3/8'' \times 3/8'' \times 4''$
 Density 5.2 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg) $\times 10^6$	$X_g \frac{788 \times \text{gain}}{H^2}$	$4 \pi I$
720	.518	28	42.6	2.00
1360	1.85	150	63.8	5.68
2140	4.58	405	69.5	9.75
3110	9.67	850	69.3	14.1
4340	18.8	1880	78.2	22.2
5500	30.2	2820	73.5	26.4
7470	55.7	4620	65.5	32.0
8320	68.0	5950	68.9	37.5
9920	98.2	7500	60.3	39.2
8340	69.3	6070	69.2	37.7
7480	55.8	4930	69.7	34.1
5730	32.7	3470	83.5	30.2
4380	19.2	2490	102	29.2
3390	11.4	1785	123	27.3
2380	5.67	1170	163	25.3
1640	2.68	784	232	24.8
900	.81	407	396	23.3
Reverse				
2400		0	0	0
4310	18.5	1700	71.3	20.4
5500	30.2	2670	70.0	24.8
7470	55.7	4430	64.3	31.7
8320	68.0	5860	64.6	36.8
9920	98.2	7500	60.3	39.2

TABLE XIV

Susceptibility and H_c data for Michigan hematite no. 1

Size $3/8'' \times 3/8'' \times 4''$
 Weight 29.3 grams
 Density 5.2 gms./cm³

H	Gain (mg.)	H_c	$X_g \times 10^6$	$4 \pi I$
650	25	320	43.7	1.86
990	59	460	49.8	3.22
1150	83	490	51.7	3.89
1310	120	630	57.8	4.95
1520	182	680	64.3	6.39
1680	238	850	69.7	7.67
1860	323	900	72.3	7.80
2000	365	990	75.3	9.89
2360	516	1120	76.4	11.8
2600	790	1540		
3040	910	1480	81.8	16.3
3400	1180	1700	84.6	18.8
3600	1330	1800	84.6	19.9
4080	1620	1860	80.0	21.3
4330	1745	1920	76.7	21.7
4560	1850	1960	73.5	21.9
4750	2020	1980	72.8	22.6
5470	2620	2040	72.2	25.8
6640	3830	2320	71.9	31.1
7530	4900	2320	71.5	35.2

TABLE XV

Susceptibility and H_c data for Michigan hematite no. 2

Size -200 mesh
 Weight 9.40 grams
 Length 11.7 cm.
 Density 2.54 gms./cm³

H	$H^2 \times 10^{-6}$	Gain (mg.)	$X_g \times 10^6$	$4 \pi I$
575	.330	44	326	6.0
1230	1.52	196	316	12.4
1960	3.85	295	315	21.0
2990	8.97	619	303	29.0
4150	17.2	990	141	18.7
5340	28.5	1460	125	21.4
6430	41.3	1950	116	23.8
7180	51.4	2270	108	24.8
8670	75.0	3080	101	28.0
9800	96.0	3605	92	28.8
8680	75.1	3130	102	28.3
7260	52.8	2510	116	26.9
6500	42.2	2160	125	26.0
5560	30.8	1770	141	25.1
4320	18.6	1230	162	22.4
3200	10.9	890	212	21.9
2310	5.33	570	262	19.4
1610	2.59	360	341	17.6
910	.825	163	479	14.0
Reverse				
1960	3.85	98	62	3.90
2990	8.97	304	83	10.6
4150	17.2	755	108	14.4
5340	28.5	1380	119	20.3
6360	40.5	1780	108	22.0
7180	51.4	2100	100	22.9
8670	75.0	3010	98	27.1
9820	96.3	3530	91	28.5

TABLE XVI

Variation of coercive force with grain size
magnetized in fields of 8,000 to 9,000 oersteds

a. Cumberland hematite

<u>Grain size, microns</u>	<u>H_c, oersteds</u>
0 - 5	2240
5 - 10	580
10 - 20	1630
20 - 40	1560
40 - 74	1300
74 - 592	1225
592 - 1650	1200

b. Michigan hematite no. 1

<u>Size</u>	<u>H_c</u>
0 - 5 microns	2340
-40 +100 mesh	2340
-200 mesh	2340
Solid block	2400

c. Michigan hematite no. 2

<u>Size</u>	<u>H_c</u>
-200 mesh	1400
-40 + 100	1140
-28 + 100	1140

d. C. P. ferric oxide

<u>Size</u>	<u>H_c</u>
Precipitated	2010

TABLE XVII

Variation of remanence with packing density.
 Cumberland hematite magnetized in fields of
 approximately 8,000 oersteds

Packing density, gm./cm ³	B_r , gauss	Grain size, microns
1.13	2.1	0 - 5
1.28	4.0	5 - 10
2.30	5.8	0 - 5
2.76	6.5	10 - 20
3.13	7.3	20 - 40
3.52	8.0	40 - 74
3.64	8.0	592 - 1650

TABLE XVIII

Thermomagnetic data for Cumberland hematite
0 - 5 microns

Temp. ° C.	Balance current, milliamperes	$\chi_g \times 10^6$
18	47	
100	47	
200	48	
300	49	
410	50	
500	53	
555	53	
590	47	
660	39	
693	27	
720	27	22
695	27	
682	36	
668	41	
615	48	
555	50	
510	50	45
420	50	
300	50	
100	50	
18	50	

TABLE XIX

Thermomagnetic data for Cumberland hematite
0 - 5 microns

<u>Original loop</u>		<u>: After cooling in magnetic</u>	
H in	: Balance	:	<u>field from Curie point</u>
oersteds	: current	:	<u>:H in oersteds : Balance current</u>
1600	9	1600	20
2350	15	2350	24
3100	21	3100	29
3850	27	3850	34
4640	31	4640	38
5270	34	5270	43
5840	40	6320	48
6320			
7020	47		
7900	54		
8360	57		
8920	60		
7900	55		
5840	44		
4640	36		
3100	28		
1600	16		
Reverse		Reverse	
2350	3	3850	10
3100	9	4640	18
4640	23	5270	24
5840	34	5840	31
7020	45	7020	43
7900	52		
8920	60	8920	60
7900	55	6320	48
5840	44	5270	43
4640	36	4640	38
3100	28	3850	34
1600	16	3100	29
Reverse		2350	24
2350	4	1600	20
3100	9	Reverse	
4640	23	3850	10
5840	34	4640	18
7020	45	5270	24
7900	52	5840	31
8920	60	7020	43
		8920	60

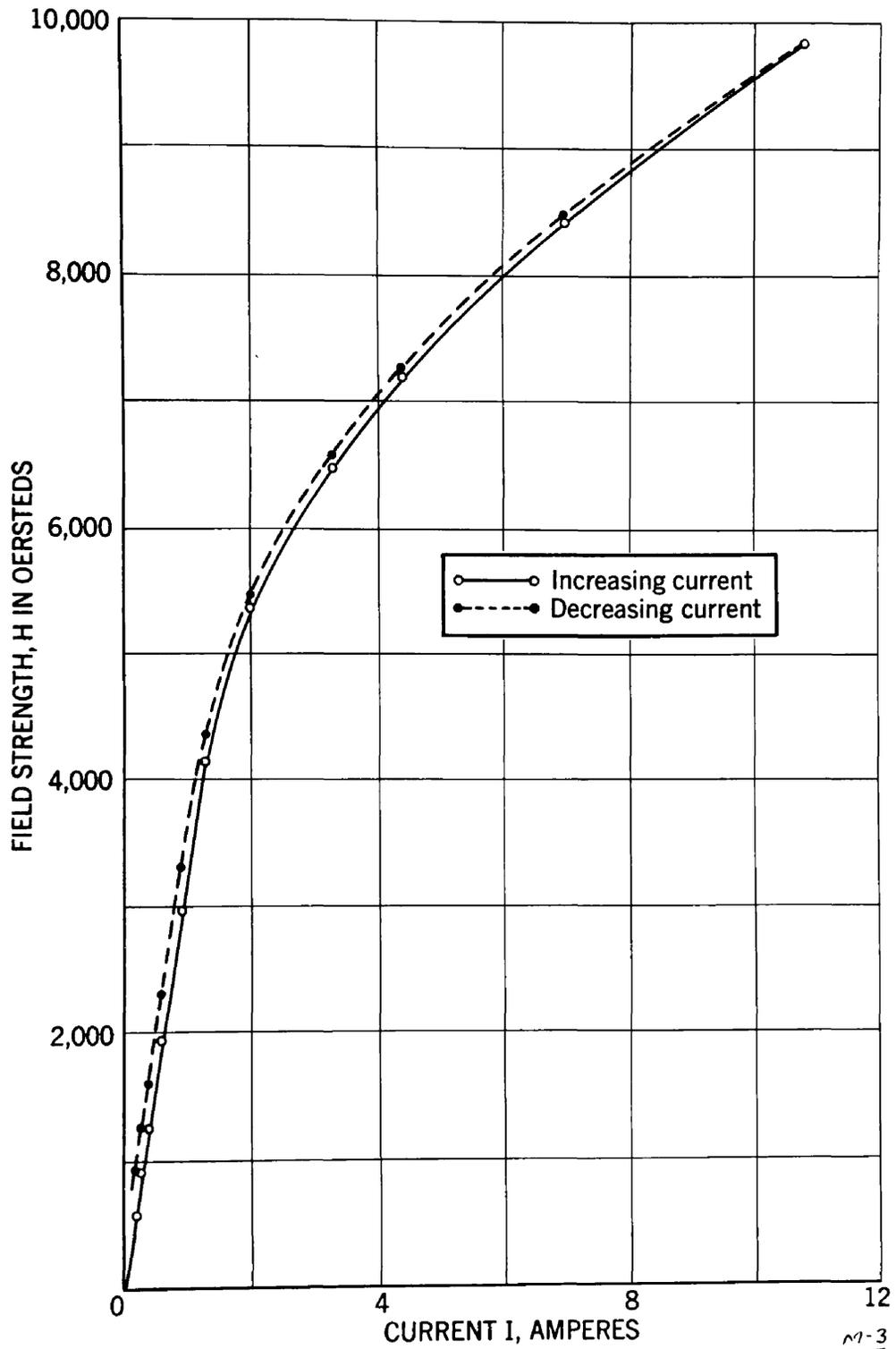


Figure 4 .—Magnet calibration.

$\frac{M-3}{45}$

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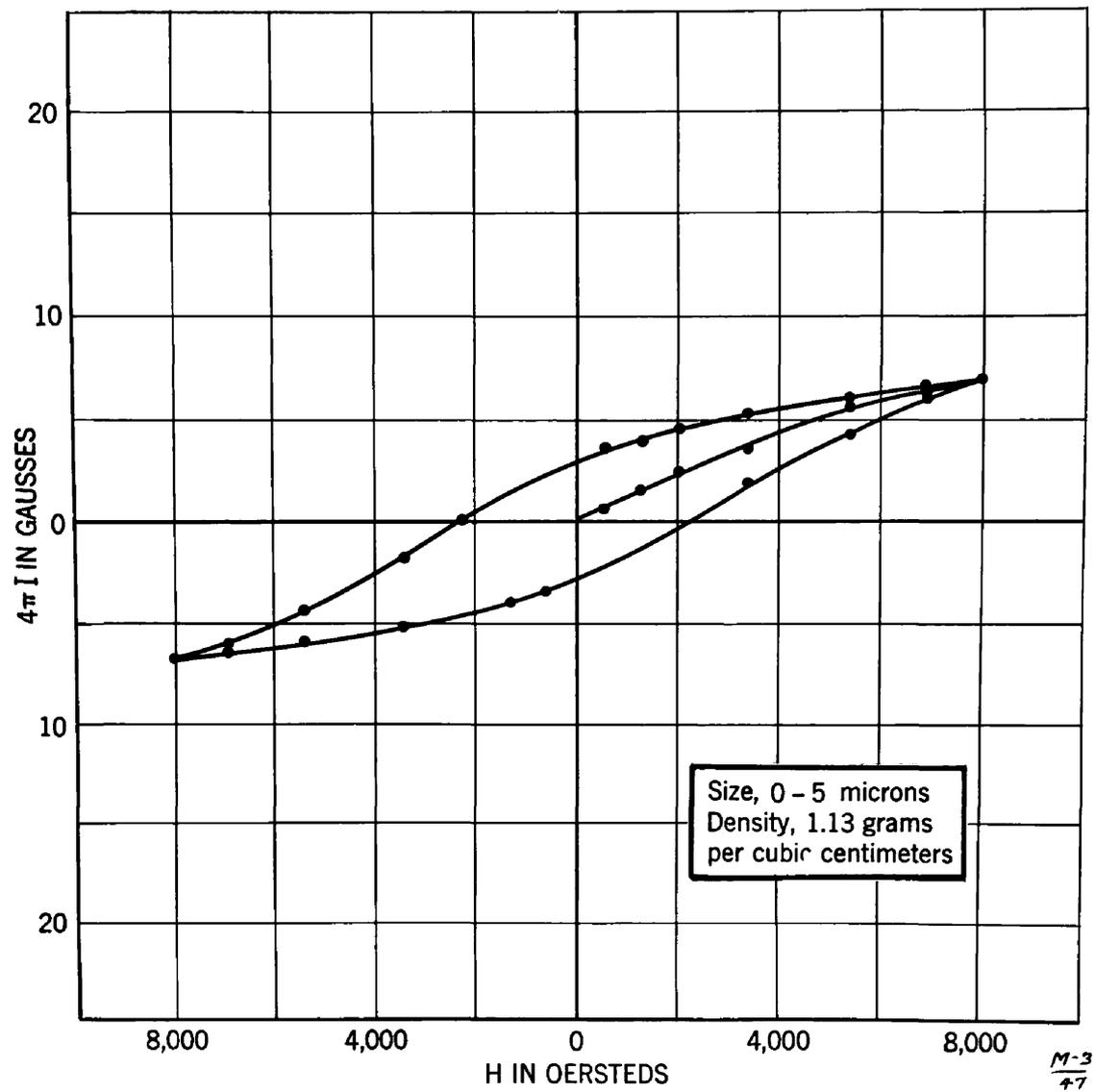


Figure 5 .→ Susceptibility data for the Cumberland hematite, size 0-5 microns, density 1.13.

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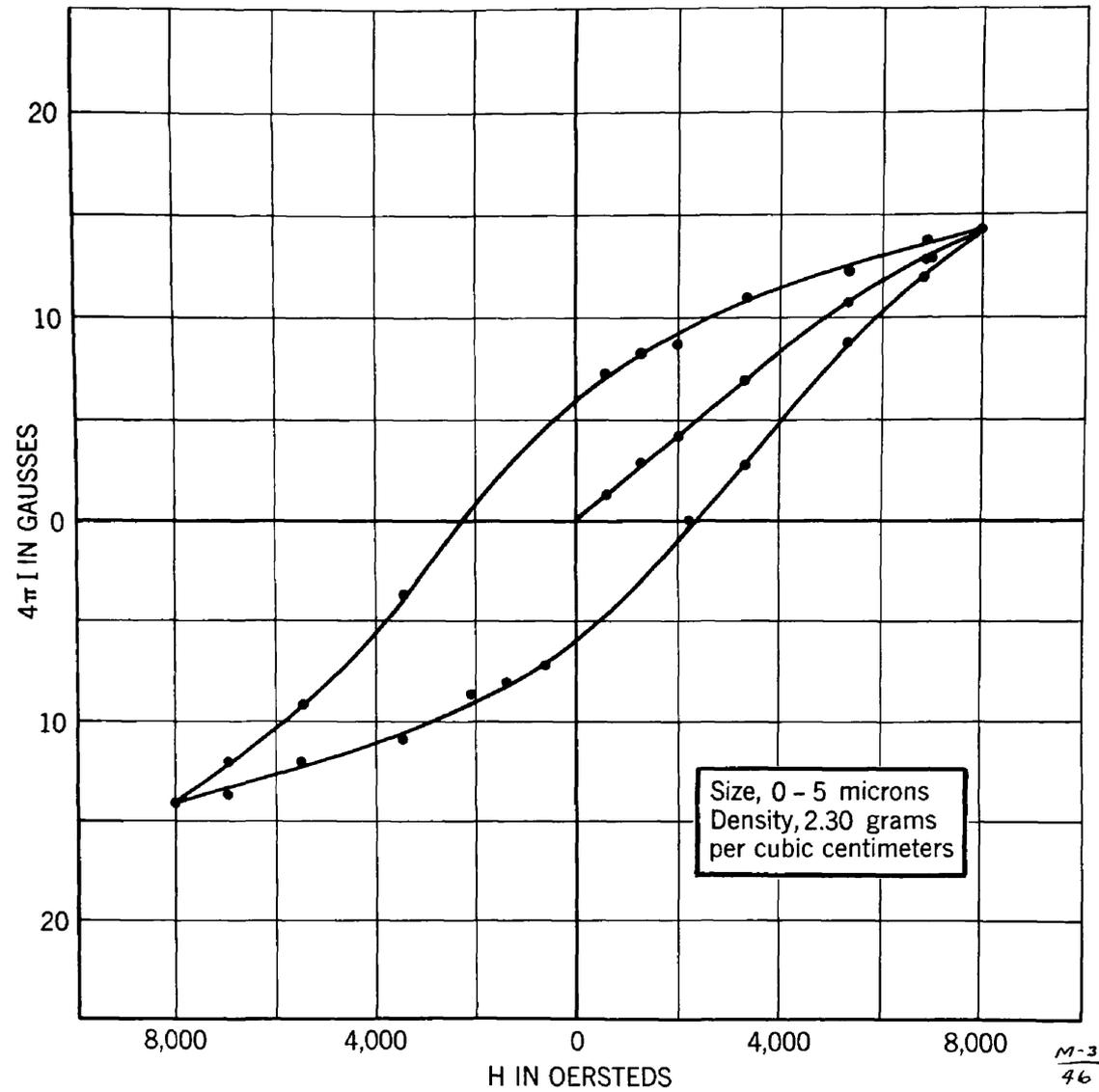


Figure 6 .—Susceptibility data for the Cumberland hematite size 0-5 microns, density 2.30.

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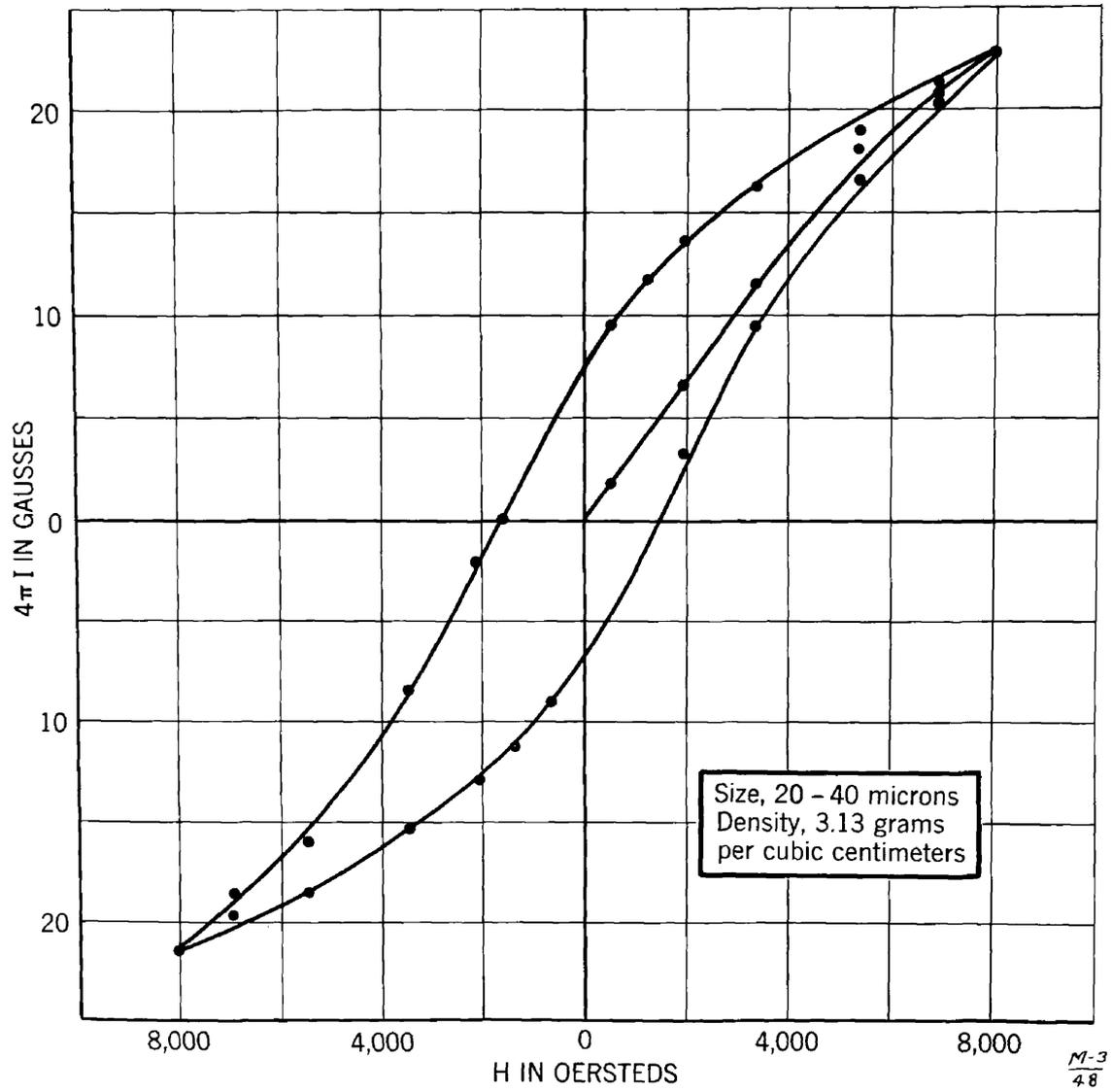


Figure 7 ---Susceptibility data for the Cumberland hematite, size 20-40 microns.

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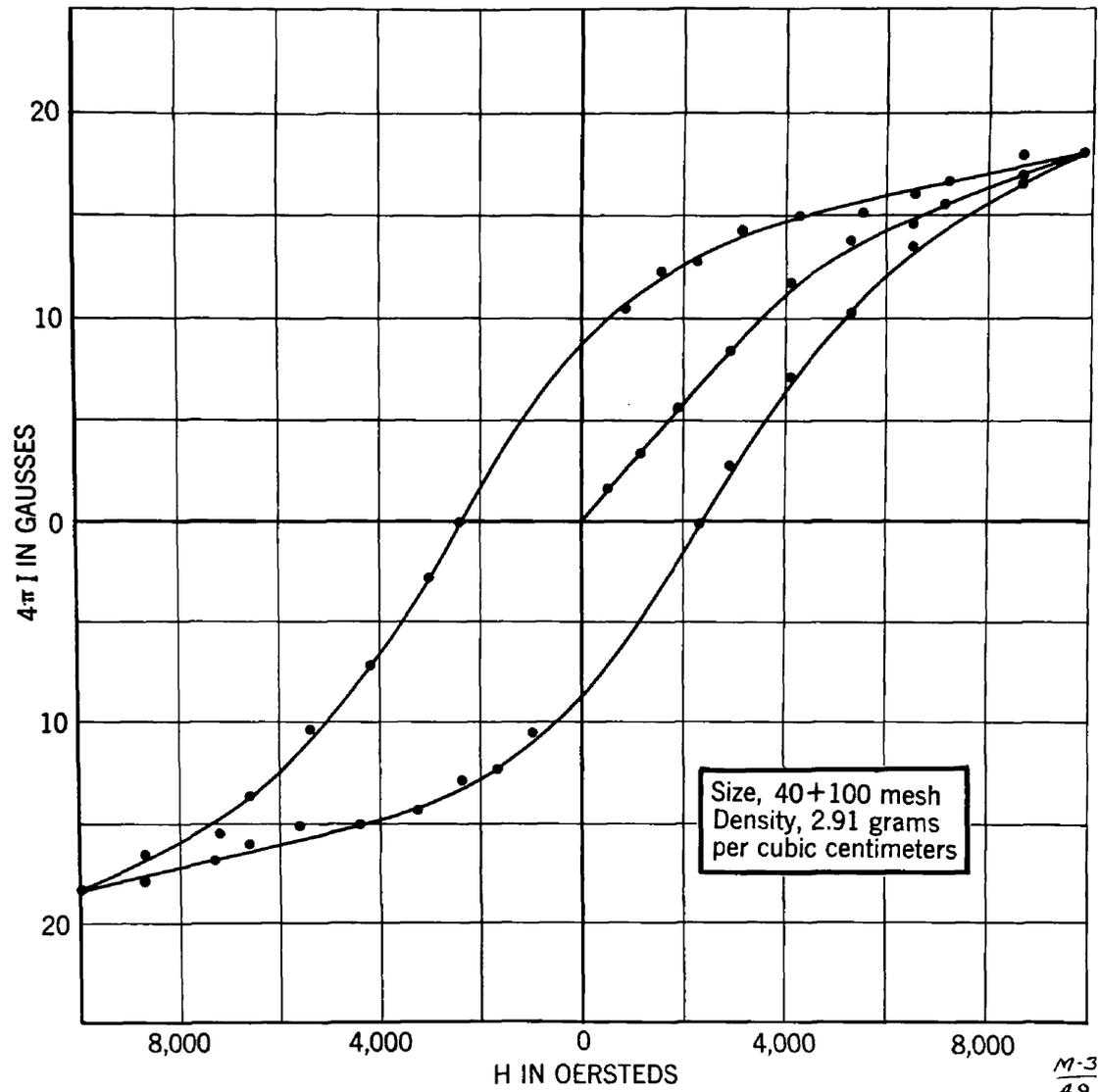


Figure 8 .—Hysteresis loop for Michigan hematite No. 1.

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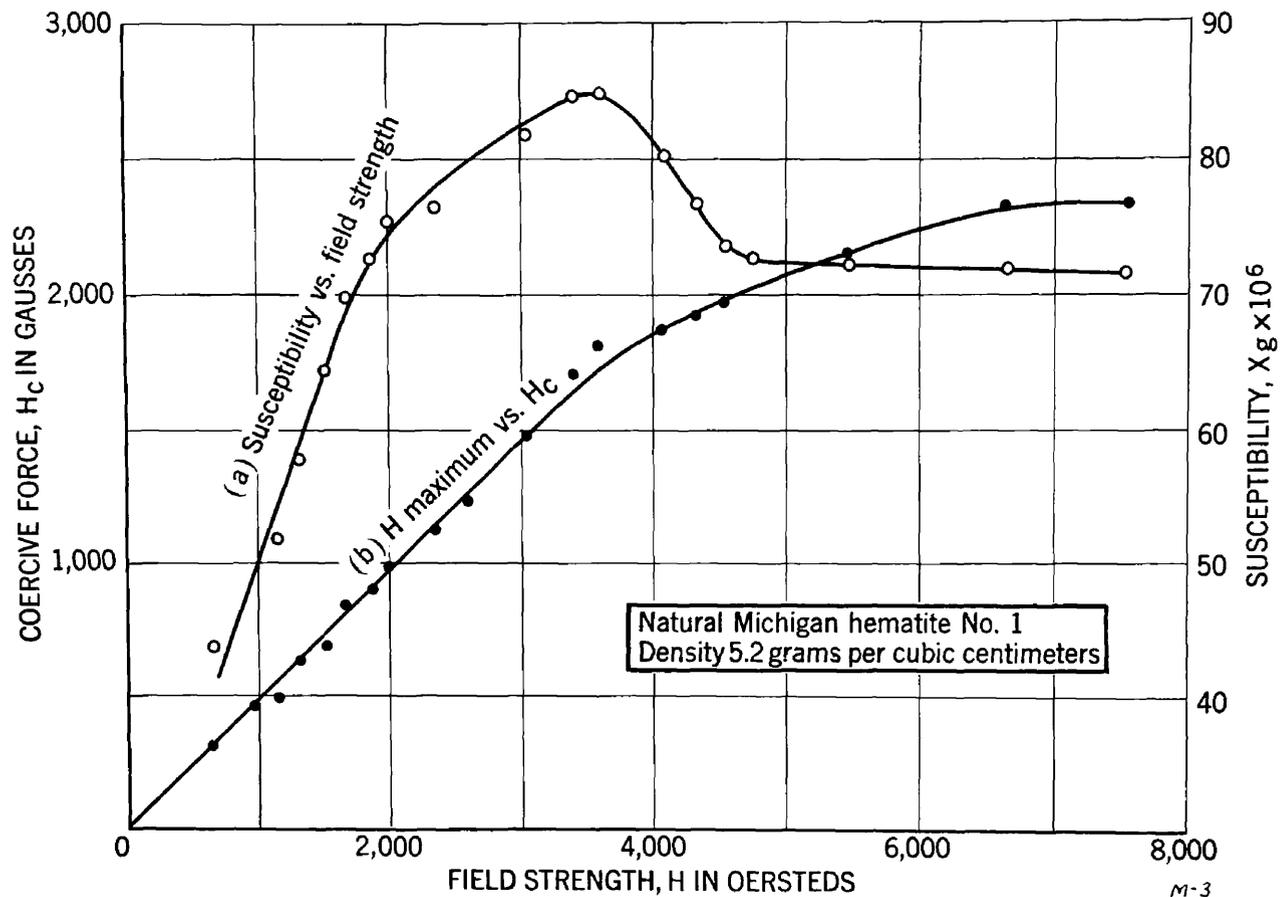


Figure 9 .—Ferromagnetic curve for hematite and relationship.
 (a) Ferromagnetic curve for hematite. (b) Relationship between magnetization and demagnetization forces.

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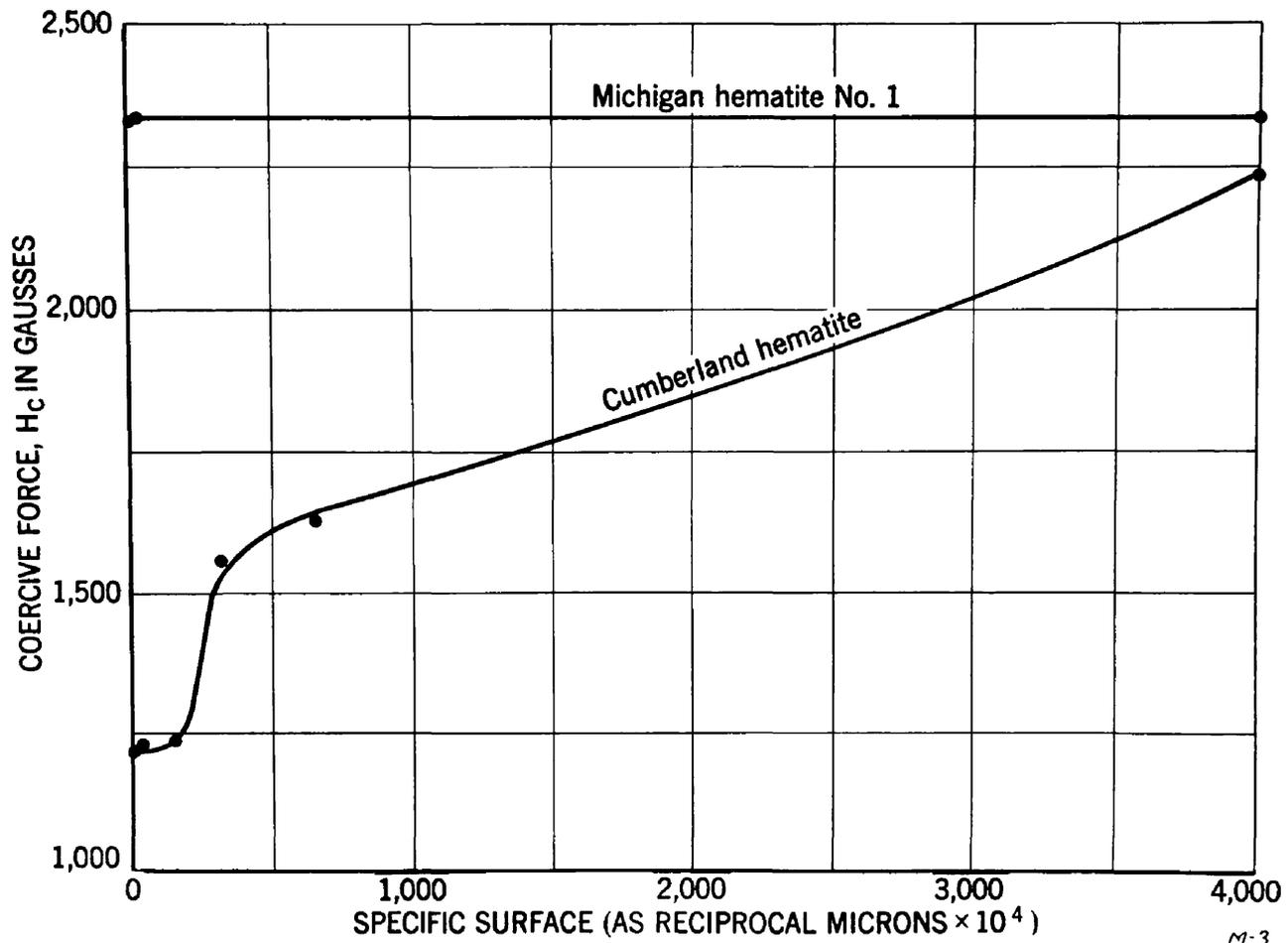


Figure 10 .—Relation between specific surface and coercive forces.

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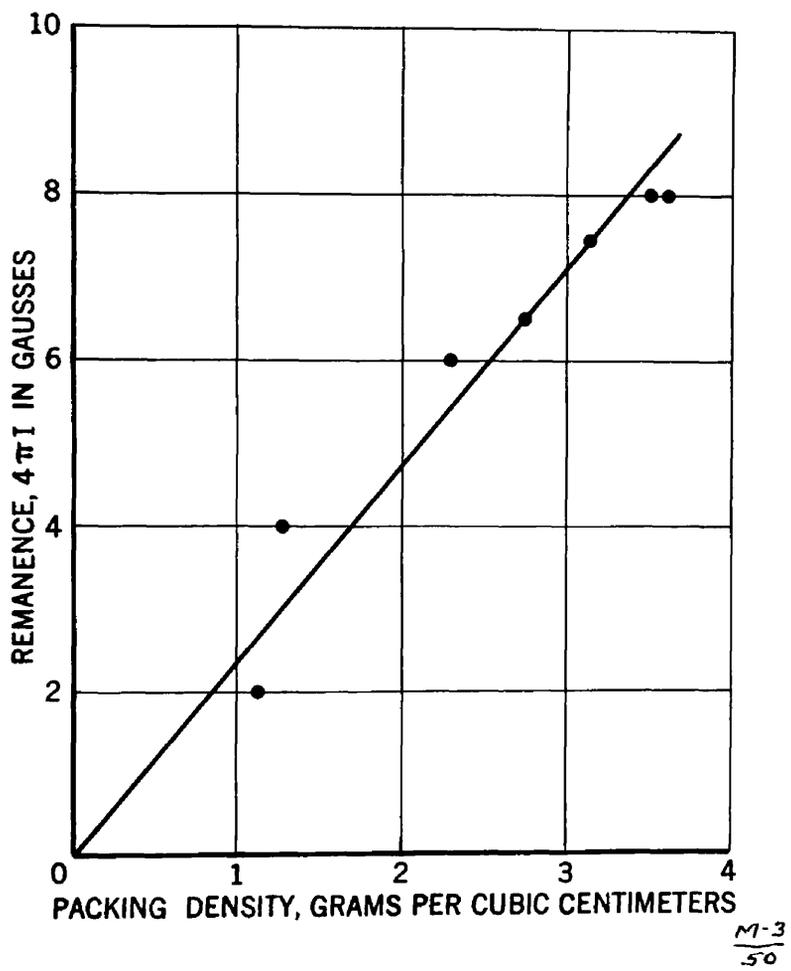


Figure 11.—Relationship between packing density and remanence of Cumberland hematite.

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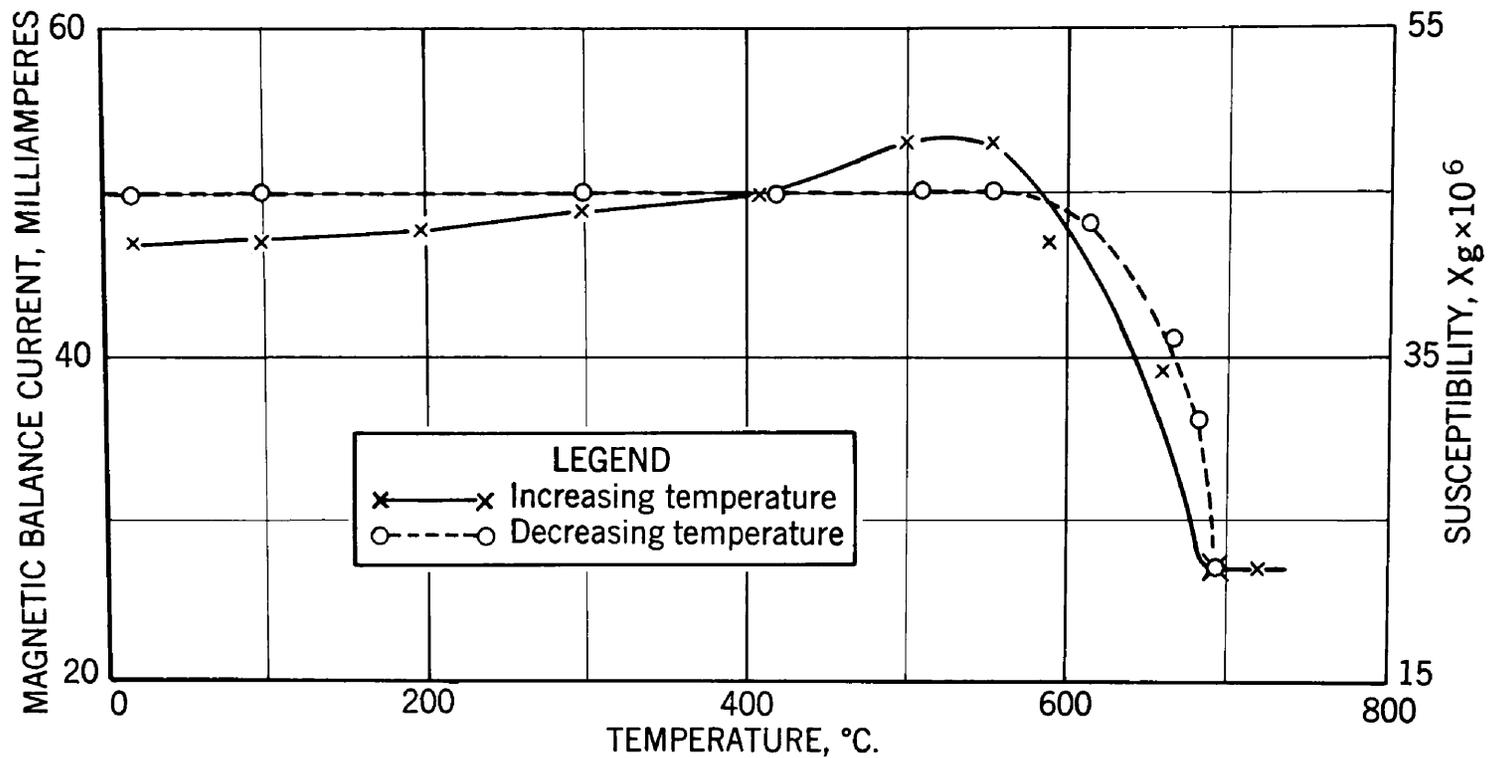
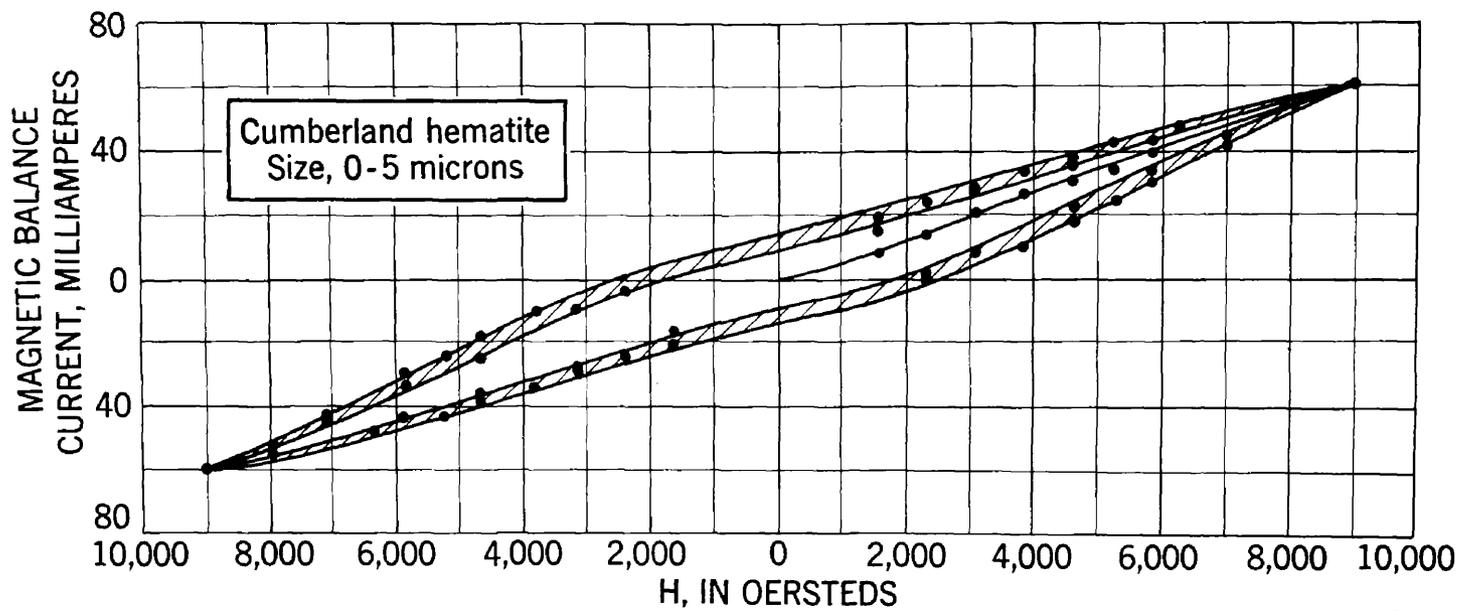


Figure 12 .—Thermomagnetic curve for the Cumberland hematite size 0-5 microns. $H = 7,000$ oersteds.

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$\frac{M-3}{51}$

Figure 13.—Effect on hysteresis loop of cooling hematite from its Curie point in a magnetic field.

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DISCUSSION OF RESULTS

Susceptibility. The ferromagnetic nature of hematite may be deduced from the shape of the susceptibility vs. field strength curves. Most of the pure hematite fractions used had a range of susceptibility values of $X_g = 40$ to 100×10^{-6} , while some of the magnetically contaminated hematites showed susceptibility values as high as 300×10^{-6} in fields below 2,000 oersteds. Most of the X_g values are from 40 to 60×10^{-6} in the lower fields and these agree substantially with the results of other investigators. Most workers in this field have tended to regard hematite as paramagnetic⁴³ and therefore usually only one susceptibility value per sample is quoted in the literature. This single value was computed from measurements at comparatively low fields of 400 to 700 oersteds and hence provides only a rough check on the susceptibility values determined in this investigation. The data in tables III to XVI indicate that the maximum susceptibility of pure hematite occurs in fields ranging from 1,500 to 3,500 oersteds, with a probability that the higher figure is more nearly correct as the following considerations show. According to Gottschalk⁴⁴ the maximum susceptibility of magnetite is attained in fields less than 13 oersteds, while Davis'⁴⁵ results show that the maximum susceptibility for gamma hematite is found in fields less than 6 oersteds. The presence of either Fe_3O_4 or gamma Fe_2O_3 in

⁴³ A paramagnetic substance is one whose susceptibility does not change with field strength.

⁴⁴ See footnote 25d.

⁴⁵ C. W. Davis. Magnetic Properties of Minerals and Their Significance. Report of Investigations 3268, Bureau of Mines, p. 93.

a hematite would tend to make the maximum occur at lower fields and would shift the upper curve in figure 9 to the left. That this fact offers a means of determining magnetic impurities in small amounts is well shown in the results in table XV. The susceptibilities determined for this hematite are all high and, as might be expected, the maximum permeability occurs at a low field strength somewhere below 600 oersteds, indicating the presence of Fe_3O_4 or gamma hematite in appreciable amounts. Although this method of determination of magnetic impurities could undoubtedly be worked out in greater detail, it is unfortunate that it does not differentiate between amounts of the different magnetic constituents. In effect Benard advocates this same principle to show the presence of Fe_3O_4 in FeO .⁴⁶

It is therefore quite probable that pure hematite has a maximum susceptibility in the neighborhood of 3,500 oersteds and that small amounts of magnetic impurities rapidly shift this maximum to lower fields. The peak in susceptibility at such high fields shows hematite to be ferromagnetic because other possible magnetic impurities have long since passed their points of maximum intensity of magnetization.

Chevalier and Mathew⁴⁷ have investigated the variation of susceptibility with grain size and found that as the grain size decreases, the susceptibility decreases. At 500 microns their hematites

⁴⁶ Jacques Benard. Etude de la Decomposition du Protoxyde de Fer et des ses Solution Solides. Annales de Chimie, 12, 1939, p. 19.

⁴⁷ Raymond Chevalier and Mlle. Suzanne Mathew. Variation of the Magnetic Susceptibility of Hematite Powders as a Function of the Size of the Grains. C. R. 204, 1937, pp. 854-856.

had a susceptibility of 400×10^{-6} and near 0 micron about 30×10^{-6} . Even excluding experimental error, the susceptibilities of the various Cumberland hematites shown in tables III to X indicate no such variation. There are two possibilities that might account for this discrepancy: (1) Chevalier may have used a very impure hematite, as indicated by high initial susceptibilities, or (2) the work may have been performed at such low field strengths, say 400 to 600 oersteds, that the variations would not be appreciable in the fields used in this work. Neither of these explanations is very probable and the whole problem may be summed up in Chevalier's words:

L'origine de cette diminution de susceptibilite
avec la taille des grains reste inconnue.

Hysteresis loops. The hysteresis loops for hematite are unique and probably without parallel in ferromagnetism--at least as far as the present knowledge of the writer is concerned. These curves were plotted as H vs. $4 \pi I$ because a $B-H$ plot would be meaningless. The $4 \pi I$ term is so small compared to H that a $B-H$ curve would be practically a straight line inclined at 45° passing through the origin. Had the same scale been used for both H and $4 \pi I$, the curve would have almost coincided with the H axis. The scales were chosen to bring out the hysteresis phenomena most clearly. In plotting hysteresis curves for the ordinary ferromagnetic substances H is small compared with $4 \pi I$ and generally can be neglected. The values of $4 \pi I$ and H_c for hematite are almost opposite in magnitude to those of metallic ferromagnetics for which the residual magnetism may be several thousand gauss when magnetized in fields of less than 15 oersteds.

The wide difference in scales used for $4\pi I$ and H make it somewhat difficult to ascertain whether hematite is approaching saturation in fields of 8,000 to 10,000 oersteds. An analysis of the coercive forces, however, indicates that at these field strengths the hematite was near saturation. The existence of a ferromagnetic substance having the combination of a coercive force of 1,100 to 2,400 oersteds with the very low remanence of 3 to 12 gaussess suggests the desirability of a more precise definition of ferromagnetism. The usual treatment of ferromagnetism almost invariably emphasizes the higher degree of magnetic effect as compared with paramagnetism. But the susceptibility of hematite is not unusually high since a few substances of mass susceptibility as high as 300×10^{-6} are known, so that in the present instance we are dealing with a ferromagnetic in the range of susceptibility values usually assigned to paramagnetics. A definition of ferromagnetism that would include hematite and at the same time would describe the salient characteristics of the commoner ferromagnetic substances should be based on the fact that only ferromagnetic substances exhibit the phenomena of residual magnetism and coercive force; that is, a ferromagnetic substance is one that retains some residual magnetism after the magnetizing force is removed and that requires a definite coercive force to reduce this residual magnetism to zero. This definition would include weakly ferromagnetic material like hematite or certain Cu-Mn alloys.

⁴⁸ Some Cu-Mn alloys studied by the author showed a range in X_g ranging from 10×10^{-6} to 200×10^{-6} in fields from 300 to 2,000 oersteds. The X_g vs. H curve shows such alloys to be ferromagnetic.

The area of the hysteresis loop is largely controlled by the packing density as shown in figures 5 and 6, where the density was the only variable.

Remanence. The values of residual magnetism obtained for hematite on magnetizing in fields of 8000 to 10000 oersteds vary from 2 to 12 gauss. This extremely low remanence indicates the difficulty of determining the magnetic properties of hematite, and explains sufficiently the incomplete state of our present knowledge of the ferromagnetic nature of hematite. The usual magnetic measurements are not very accurate when the permeability is less than 1.1 and the magnetometer is not very useful at permeabilities less than 1.003. A rotating coil method might have been used to measure this remanence but an instrument delicate enough to register such low values of intensity of magnetization could not be used in fields of the order of 1100 to 2400 oersteds needed to reduce the magnetization to zero.

Figure 11 shows that the remanence is a direct function of the packing density, bearing out the well known fact that the volume susceptibility $k = \text{mass susceptibility, } X_g, \times \text{ apparent density of material tested}$. Slight deviations are due to impurities and errors in interpolation of the point where the hysteresis curve crosses the $4 \pi I$ axis.

This low remanence is another indication that although hematite is ferromagnetic, the differences in susceptibility for small increases in magnetization are so small that hematite could easily be mistaken for a paramagnetic. Small as it is, the existence of remanence is indisputable proof of the ferromagnetic nature of hematite.

The effect of time on the remanence values was not studied beyond a few qualitative tests which showed that the blocks of hematite still retained about 90 percent of their remanent magnetism after two months' time.

Coercive force. The values of coercive force found are the highest known in any natural mineral and, in fact, the higher value of 2,400 oersteds is of the same order as found only in the very best of the recently discovered permanent magnets.

The variation of coercive force with size of particles in powders cannot be explained satisfactorily by the present theories of magnetism. Table XVI shows that for Cumberland hematite there is a change of coercive force with grain size and the results are plotted in figure 10. This curve shows that the coercive force slowly increases with increasing surface until a grain size of approximately 50 microns is reached. There is then a rapid increase in H_c for a small increase in area and after that a gradual increase as the grain size becomes extremely small.

Because of the small amount of research done on mineral physics our knowledge of the magnetic properties of minerals is rather meager and offers little opportunity for comparison or correlation of such phenomena. Gottschalk⁴⁹ has shown that there is a straight-line relationship between H_c and grain size for magnetite and this principle has been used in research for determination of surface produced by grinding.⁵⁰

⁴⁹ See footnote 25d.

⁵⁰ Fred DeVaney and Will H. Coghill. Use of the Coercimeter in Grinding Tests. A.I.M.M.E. Tech. Paper 862, 1938.

There is no such linear relationship for Cumberland hematite. One point of interest is that the greatest change of H_c takes place at about 50 microns, which is the same size at which Chevalier⁵¹ noticed the greatest change in susceptibility with grain size. In the limited number of tests made on other hematites, Michigan no. 2 indicates the same trend as Cumberland hematite, as shown in table XVI, but it was not sized fine enough to find out the exact relationship. The C.P. ferric oxide has a high H_c , as one might expect since the grain size is of almost molecular dimensions. The surprising part of this work is that Michigan hematite no. 1 showed no indication of change in coercive force over a grain size range from 0-5 microns to pieces of ore 3/8" square. The question naturally arises then as to what constitutes "magnetic surface". It would appear that there is some limiting crystal size of mineral that is associated with normal magnetic properties. When the crystal is reduced to a powder, new surface is exposed with a change of magnetic properties. This might be likened to surface tension in liquids which is caused by an unbalancing of forces at the surface of the liquid. If the liquid is spread over a larger area, the free energy in the system is increased and a larger force acts over the total surface. In minerals the increase in free energy (crushing and grinding) produces new surface down to some unit magnetic crystal. When this crystal is broken into powder form, the surface tension or coercive force increases because more free energy has been added to the system to make up for the unbalancing of magnetic moments at the surface. The

⁵¹ See footnote 47.

remanent magnetism is more tightly held, and therefore requires a greater coercive force to reduce it to zero. This theory would indicate that the unit magnetic crystal in Michigan hematite no. 1 must be less than 1 micron and that the specimen is extremely polycrystalline. Time did not allow an X-ray examination of these hematites to ascertain difference in crystal structure but some such relationship probably exists because there is a parallel case in the manufacture of permanent magnets. The magnetic materials are mixed for the magnets and then given a proper heat treatment to produce a magnet with certain remanence-coercive force characteristics. This heat treatment is probably a dispersion of certain materials in the alloy to vary the "magnetic surface".

Curve b in figure 9 represents an attempt to find the H_c of hematite at saturation by means of Kennelly's law. This law is a restatement of Frohlich's relationship, which says that "the permeability is proportional to the magnetizability". It follows from this law that $\frac{H_{max}}{H_c} = a + b H_{max}$.⁵² Obviously the results shown in figure 9 do not fit any straight line over the entire range. Qualitatively they indicate that hematite is near saturation in fields of 10,000 oersteds. Attempts to make use of a similar relationship between B_r and B_{max} meet with even less success.

The H_{max} vs. H_c curve shows that in the case of this hematite there is a linear relationship between the magnetizing and demagnetizing

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R. L. Sanford and W. L. Chaney. The Variation of Residual Induction and Coercive Force with Magnetizing Force. Scientific Paper of Bureau of Standards no. 384, 1920.

force up to maximum susceptibility at about 3,500 oersteds. Past this point of maximum susceptibility the H_c drops rapidly with increasing H_{max} . The curve shows that at this place there exists the maximum intensity of magnetization. Past this point it is much more difficult to turn the magnetons a few more degrees for absolute lining up with the applied field. Whereas it may take several thousand oersteds past I_{max} to line up the magnetons, the additional H_c is small because of the small amount of turning done by the magnetons. The large H_c values show that commercial demagnetization would be extremely difficult. In fact, this material could not even be demagnetized in the laboratory. Theoretically it could have been demagnetized if the H_{oc} were known. Practically, this was almost impossible.

Thermomagnetic measurements. The thermomagnetic curve shown in figure 12 for hematite has been determined frequently; the curve has the same general form as the one given by Rogers and Stamm.⁵³ The paramagnetic value for susceptibility above the Curie point, which is called the paramagnetic susceptibility, was found to be 22×10^{-6} , a little higher than the average value of 20×10^{-6} given by Chevalier and Begui;⁵⁴ errors in zero correction on the balance would probably account for this difference. The Curie point of about 685°C . is in accord with the accepted value for Fe_2O_3 .

⁵³ See footnote 16.

⁵⁴ Raymond Chevalier and Z. Esmail Begui. Thermomagnetic Properties of Ferric Oxide. Soc. Chimique, November 1937, pp. 1735-41.

A hysteresis loop was run on the material before heat treatment and the results are shown in the smaller loop of figure 13.

The shape of the hysteresis curve shows that the method developed in this investigation is valid for both types of magnetic balances. The material was then heated to its Curie point of 685° and cooled in a magnetic field of about 7,000 oersteds. A hysteresis loop was then run once more and it was found that both the remanence and coercive force had increased, as shown by the outer hysteresis loop.

The interpretation of an increase in both B_r and H_c is difficult. Koenigsberger⁵⁵ has reported that magnetite acquired a remanence 100 to 1,000 times greater than the normal B_r when cooled from its Curie point in a magnetic field. Bozorth and Dillinger⁵⁶ heat-treated permanent magnet materials in a magnetic field and in some cases found an enormous increase in permeability but a loss in coercive force, all of which they attempted to explain on the basis of the domain theory. It is conceivable that the axes of all the elementary magnetons become parallel in a magnetic field when heated, because as the thermal agitation increases it becomes easier to turn the elementary magnet in the direction of the field. At, say, 1° under the Curie point, there is

⁵⁵ J. G. Koenigsberger. Stabilität der magnetischen Thermoremanenz in Tongegenständen und Gesteinen bei Bestimmungen des Magnetischen Erdfeldes in der Vergangenheit. Gerlands Beiträge Zur Geophysik, 54, Book 1, 1938.

⁵⁶ R. M. Bozorth and J. F. Dillinger. Heat Treatment of Magnetic Materials in a Magnetic Field. Physics, 6, 1935, pp. 279-85.

saturation when only an extremely small field is used. As the temperature decreases, the magnets still tend to stay parallel with the field and there is saturation at lower temperatures. It is harder to evaluate the domain contribution to such an increase in magnetism. The very nature of the domain theory would demand that tremendous fields be used during cooling if the domains are to be kept in alignment.

In the case of the hematites tested, both B_r and H_c increased slightly. Had there been a conversion to magnetite during heating B_r would have increased but H_c would have decreased due to its low value in comparison with hematite. It appears therefore that the influence of cooling in a magnetic field is real, and suggests that an explanation in terms of thermodynamic theory should be possible. No such explanation for the extra energy of the increased area of the hysteresis drop has been given, to our knowledge. This matter has practical as well as theoretical interest and merits further consideration.

Application to magnetic separation. Difficulties encountered in developing the experimental method consumed so much time that little was done on the application of the data obtaining on magnetic separation. Qualitative tests were made by suspending a paper bearing the magnetized hematite over a small alternating current field. The jumping action due to repulsion was so faint in all trials that no concentration of hematite was possible. A further study of the effect of change in field alternation might be advisable since only 60 cycle current was used in these experiments. The tremendous coercive force of hematite magnetized in high fields would allow the use of large alternating current separators and perhaps the force of repulsion could be

increased in this manner. These tests lead to the same fact—a mineral must have a fairly high coercive force and remanence to be amenable to alternating current magnetic separation. On one hand we have magnetite with a large remanence but such a low coercive force that an alternating field of any consequence demagnetizes it at each alternation, or rather, the material is so magnetically soft that the poles change with each alternation and there is no repulsion. At the other extreme is hematite which has a coercive force capable of withstanding large alternating fields but with so little remanence that the force of repulsion is too small to move the hematite particles and hence to be used in alternating current magnetic separation at the present time.

Heat treatment to alter the remanence and coercive force offers interesting possibilities. It might be possible to sacrifice part of the H_c for a gain in remanence, such as is done in the case of permanent magnets. Heating to the Curie point (680°C.) and cooling in a magnetic field might help to increase the remanence but the economics of this heat treatment would have to be compared with the present reducing roast process.

CONCLUSIONS

1. The use of the Gouy-type magnetic balance has been extended so that it is possible to measure the hysteretic constants of weakly ferromagnetic materials.
2. Alpha hematite has been shown to be distinctly ferromagnetic because:
 - a. Its X_g vs. H curve shows a maximum.
 - b. It exhibits residual magnetism.
 - c. A definite coercive force is required to reduce its remanent magnetism to zero.
 - d. It has a Curie point.
3. The hysteresis phenomena can be attributed only to hematite, and not to other ferromagnetic impurities, because of the large coercive force values and because of the maximum X_g that occurs at high fields.
4. Hematite approaches saturation in fields of 10,000 oersteds.
5. The slight repulsion of hematite from an alternating current field after magnetization in high direct current fields is insufficient for practical concentration by such means. The remanence is so low and the hematite is so near saturation in fields of 10,000 oersteds that "activating" the hematite in fields of 25,000 to 30,000 oersteds would not help very much.
6. The fact that hematite is ferromagnetic even though the susceptibility values are only those of a strongly paramagnetic substance suggests a definition of ferromagnetism based on hysteretic phenomena.